AD-767 239

GENERAL DESCRIPTION OF THE ROTORCRAFT FLIGHT SIMULATION COMPUTER PROGRAM (G-81)

Edward E. Austin, et al

Army Air Mobility Research and Development Laboratory
Fort Eustis, Virginia

June 1973

AD

AD 767239

USAAMRDL TECHNICAL NOTE 11

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U. S. ARMY AIR MOBILITY RESEARCH AND DEVELOPMENT LABORATORY
FORT EUSTIS, VIRGINIA

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UNCLASSIFIED
Security Classification

DOCUMENT CONTROL DATA - R & D		
(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)		
1. ORIGINATING ACTIVITY (Corporate author) Eustis Directorate U.S. Army Air Mobility R&D Laboratory Fort Eustis, Virginia	2a. REPORT SECURITY CLASSIFICATION Unclassified	
	2b. GROUP	
3. REPORT TITLE GENERAL DESCRIPTION OF THE ROTORCRAFT FLIGHT SIMULATION COMPUTER PROGRAM (C-81)		
4. DESCRIPTIVE NOTES (Type of report and inclusive dates)		
5. AUTHOR(S) (First name, middle initial, last name) Edward E. Austin William D. Vann		
6. REPORT DATE June 1973	7a. TOTAL NO. OF PAGES 55	7b. NO. OF REFS 9
8a. CONTRACT OR GRANT NO.	9a. ORIGINATOR'S REPORT NUMBER(S) USAAMRDL Technical Note 11	
b. PROJECT NO.		
c.	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)	
d.		
10. DISTRIBUTION STATEMENT Approved for public release; distribution unlimited.		
11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Eustis Directorate U. S. Army Air Mobility R&D Laboratory Fort Eustis, Virginia	

13. ABSTRACT

The Rotorcraft Flight Simulation is a multidisciplinary mathematical model that may be used to simulate a wide variety of helicopter or V/STOL aircraft configurations using a digital computer. Aircraft performance, stability and control, and maneuver characteristics, as well as rotor blade loads, may be estimated using this analysis. The fuselage, main rotor, tail rotor, wing, elevator, fin/rudder, jet thrust, and weapon recoil are treated as separate aircraft components, allowing detailed representation of the aircraft for design or detailed analysis applications. Six rigid-body fuselage degrees of freedom and up to six rotor blade elastic degrees of freedom for each of two rotors are accounted for.

Input for the simulation is divided into logical blocks in an easy-to-understand format. The rotor blade elastic degrees of freedom are omitted if stiffness and mass properties are not known. Output includes aircraft trim attitude, control positions, performance rotor loads, stability and control characteristics, and detailed maneuver response.

While correlation of the predicted results from the Rotorcraft Flight Simulation is generally satisfactory, especially for single-rotor helicopters, no detailed comparison with blade loads test data has been made. Current development of the analysis includes such a correlation as well as an investigation of advanced control systems, development of an improved unsteady aerodynamic representation, the inclusion of a more detailed aerodynamic representation of all aircraft components, and the implementation of advanced numerical techniques that will result in reduced run times.

DD FORM 1 NOV 65 1473 REPLACES DD FORM 1473, 1 JAN 64, WHICH IS OBSOLETE FOR ARMY USE.

UNCLASSIFIED
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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Computer Program C-81						
Rotorcraft Flight Simulation						
Mathematical Model						

UNCLASSIFIED

Security Classification

6806-73

SUMMARY

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INTRODUCTION

The Rotorcraft Flight Simulation Computer Program C-81 is a highly versatile digital flight simulator that may be used to study steady-state and maneuver performance, rotor loads, stability and control, aircraft attitude and flight path, gust response, and many other aircraft characteristics. This report describes, without exhaustive analytical detail, the history, content, use, and current development of the Rotorcraft Flight Simulation program. The analysis and use of the program are further explained in References 1 through 7.

HISTORY

The C-81 family of helicopter flight simulation programs has been under development by Bell Helicopter Company and the Government for the past decade (Figure 1). Throughout this development, certain guidelines have been followed. First, the analysis is sufficiently general to describe a wide variety of helicopter configurations (conventional, compound, tandem, side-by-side) for a broad range of flight conditions (hover, transition, cruise, high speed, maneuver). The overall analysis has a uniform texture; i.e., the level of complexity of the different phases (aerodynamic, dynamic, rotor analysis, etc.) is uniform. The program is applicable to diverse types of analysis such as performance, stability and control, and rotor loads. Finally, the program is user-oriented in terms of preparing the input data and interpreting the results.

The first major step in computerized analysis was a digital program to determine the overall helicopter performance and rotor blade bending moments for level-flight conditions. Aerodynamic considerations included compressibility, stall, and reversed-flow effects from two-dimensional airfoil test; separate treatment of specified radial segments with special lift and drag characteristics; and procedures to balance all forces and moments to satisfy the requirements of trimmed flight. The introduction of coupling between in-plane and out-of-plane blade deflections in the rotor dynamic analysis significantly improved the calculation of natural frequencies and forced response for rotor systems with several combinations of number of blades and types of hub construction.

The next major development of the analytical simulation included the addition of a maneuver capability with six degrees of freedom for the helicopter fuselage. Definition of the airframe was extended to include physical dimensions for cg location, mast length, and tilt; and the sizes and locations of wings, elevator, vertical fin, and pylon fairing. Contributions to lift, drag, and side forces and to pitching, yawing, and rolling moments were treated separately for each aerodynamic surface to obtain a useful method of calculating stability derivatives and maneuver capability. Control linkage ratios, engine power controls, and external gust disturbances were added to simulate a wide variety of VTOL maneuvers.

Under the contract reported in Reference 2, the simulation was further expanded to encompass all of the basic rotorcraft configurations: single main rotor plus antitorque tail rotor, tandem, side-by-side tilting rotor, and coaxial. The detailed aerodynamic and dynamic treatment of the second rotor, plus provisions for locating, orienting, and controlling both of the rotors, led to an all-purpose, generalized analytical ability. Two-, three-, and four-bladed rotors were considered for hub types that were either teetering, gimbaled, articulated, or rigid (hingeless). The effects of gradual penetration of a shaped gust field by the rotor disc were added to the analysis and evaluated during the course of the study.

In 1969, under an Air Force contract, a version of the analysis was prepared with a special treatment of the rotor dynamics to allow the study of slowed- and stopped-rotor VTOL configurations. A time-variant analysis was added that accounts for the rigid-blade flapping motions of up to, and including, seven blades while simulating teetering, gimbaled, articulated, or rigid hub configurations.

A time-variant aeroelastic rotor response analysis based on the modal technique was incorporated into the program during a USAAMRDL-sponsored project, providing improvements that are directed, principally, toward a better analytical capability for studies of loads, vibrations, and transient aeroelastic behavior of rotor systems.

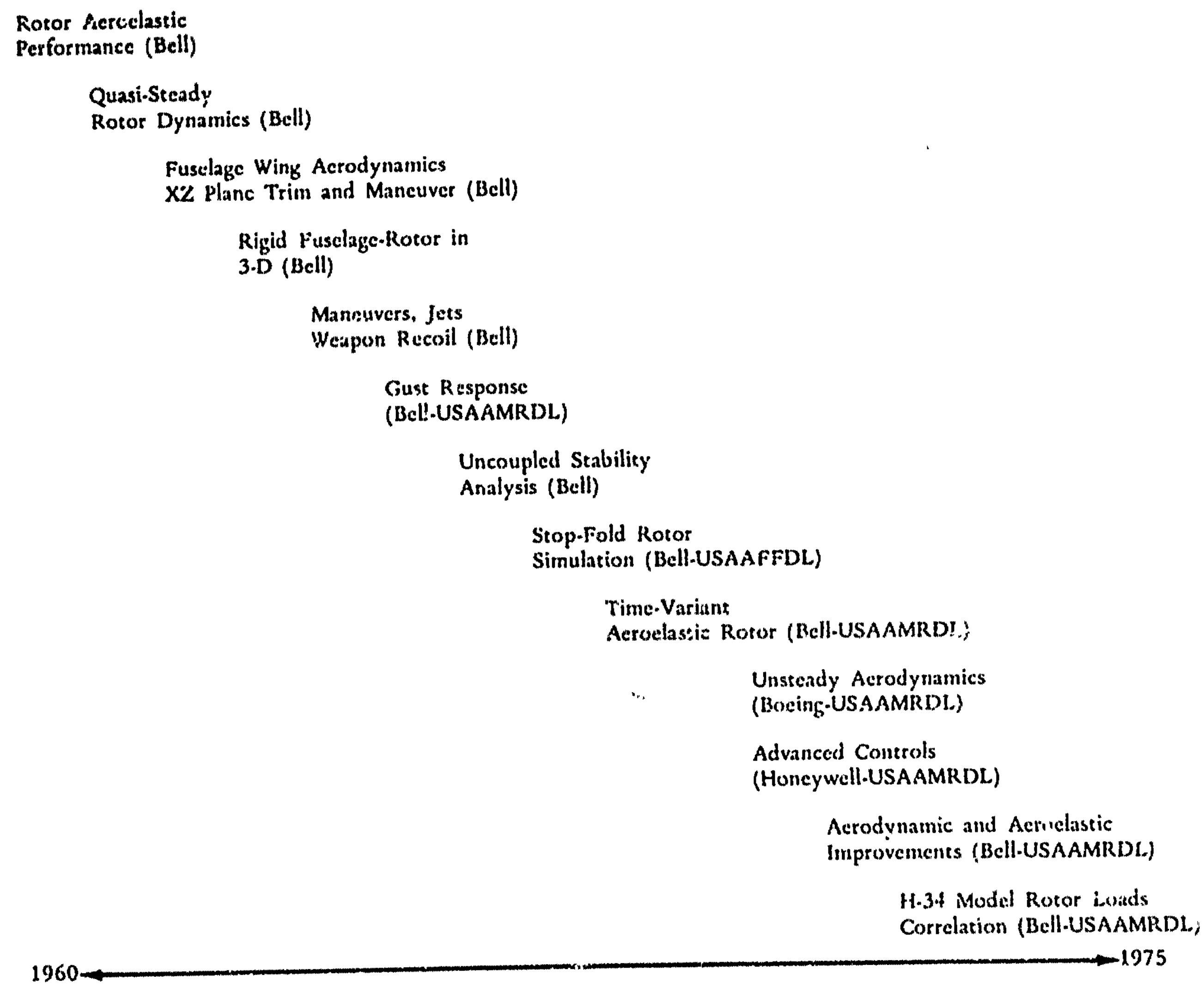

Figure 1. Rotorcraft Flight Simulation Development History.

DESCRIPTION OF MATHEMATICAL MODEL

RIGID BLADE ANALYSIS

The following description of the mathematical model applies to the version of the Rotorcraft Flight Simulation delivered under the gust response contract (Reference 2).

The aircraft fuselage is treated as a rigid body that is subject to gravity and applied external forces and moments due to:

1. Fuselage aerodynamics
2. Main rotor aerodynamics
3. Tail rotor aerodynamics
4. Wing aerodynamics
5. Elevator aerodynamics
6. Fin/rudder aerodynamics
7. Auxiliary thrust
8. Weapon recoil force

These forces and moments, which act at input points of application, are transferred to the aircraft cg and summed. For trimmed, level, 1g flight, the sum of the external forces and moments and the weight must equal zero. During maneuvers, the sum is used as the forcing function in the Euler form of the equations of motion that are derived in Reference 8.

Aerodynamic forces and moments due to the wing, fin/rudder, fuselage, and elevator are calculated from the local aerodynamic environment and input constants that provide a curve fit to wind tunnel test data or to lift, drag, and moment data predicted by analytical methods. The force and moment characteristics are generally represented as functions of angle of attack and Mach number with corrections applied for yawed flow and interference effects. The forces act at center-of-pressure locations specified by the user.

The rotor strip theory aerodynamic calculations take into account an approximate nonuniform inflow as well as velocities due to airspeed, aircraft pitch rate, rotor rpm, and blade flapping. Only rigid blade flapping is included in the analysis. Blade force coefficients are functions of angle of attack and Mach number and may be input in tabular or curve-fit formats. Only blades with uniform airfoil section from blade cutout to blade tip may be represented.

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ELASTIC BLADE ANALYSIS

The analysis developed under another Army contract differs from the rigid blade analysis primarily in that treatment of rotor dynamics, hub in-plane motion, shaft windup, and rotor blade elastic bending is considered. The hub motion is represented by an upside down pendulum with a torsional spring that is driven by the in-plane blade shears and by the pitch and roll moments as shown for longitudinal motion in Figure 2.

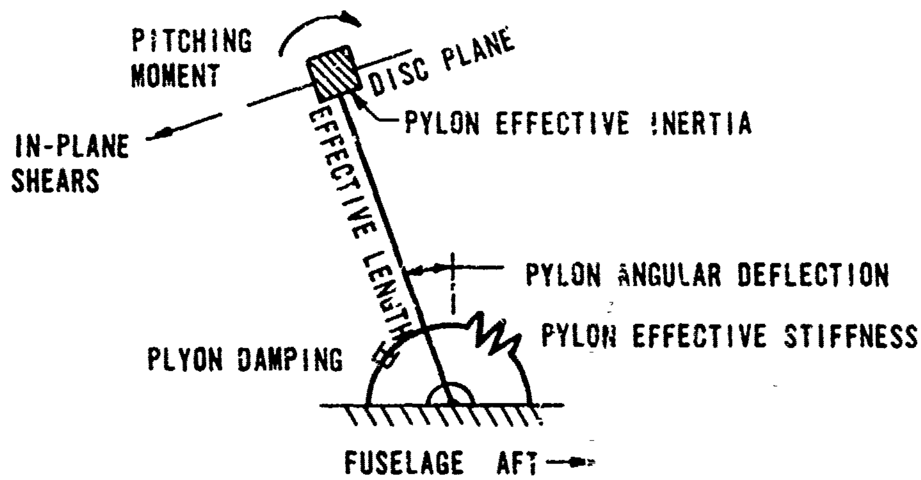

Figure 2. Model for Longitudinal Hub Motion.

The ability of the rotor shaft to twist in response to the applied in-plane torque is simulated by assuming that at the bottom of the shaft there is an infinite torsional inertia revolving at a constant speed. Connecting this large inertia with the blade is a torsionally flexible shaft with an input spring rate. The torsional deflection of the hub is then calculated from the applied in-plane blade moment.

In the rotor analysis, the elastic deformation of the rotor blades is approximated by a finite series of products of functions that vary with radius (mode shapes) and time (participation factors). For Z (the out-of-plane deflection), Y (the in-plane deflection), and θ (the torsional deflection),

$$Z(x,t) = \overline{Z}_1(x)q_1(t) + \overline{Z}_2(x)q_2(t) + \dots + \overline{Z}_n(x)q_n(t)$$

$$Y(x,t) = \overline{Y}_1(x)q_1(t) + \overline{Y}_2(x)q_2(t) + \dots + \overline{Y}_n(x)q_n(t)$$

$$\theta(x,t) = \overline{\theta}_1(x)q_1(t) + \overline{\theta}_2(x)q_2(t) + \dots + \overline{\theta}_n(x)q_n(t)$$

where $1 \leq n \leq 6$ and n is the number of modes used.

The set of functions $[\overline{Z}_i(x), \overline{Y}_i(x), \overline{\theta}_i(x)]$ is called the i^{th} mode shape of the rotor blade. Associated with each mode shape is a natural frequency, ω_i . Both the mode shapes and the natural frequencies result from the study of the rotor blade free vibration equations of motion and are used because, through them, the solution of the forced equations of motion for the blade is vastly simplified. The mode shape and natural frequencies that are inputs to the Rotorcraft Flight Simulation are computed at the Eustis Directorate by using the Myklestad program. Other installations could use other programs as long as the modes and frequencies thus calculated are put into the Rotorcraft Flight Simulation in accordance with the User's Manual instructions.

The displacements and velocities due to the hub motion, shaft windup, and elastic blade deflections are included in the calculation of blade aerodynamics, resulting in a coupled aeroelastic analysis. In addition, blade loads are calculated for trim and maneuver cases. A harmonic analysis of trimmed flight loads is also provided.

INPUT

Input to the Rotorcraft Flight Simulation (Figure 3) is user-oriented, i.e., either physical measurements taken from the aircraft or curve fits to nondimensional aerodynamic data. The program input, generally, includes:

1. Logic control cards

2. Aircraft gross weight; cg location; fuselage aerodynamic center location; aerodynamic curve-fit constants to fuselage lift, side force, and drag, and pitch, roll, and yaw moment equations

3. Main and tail rotor physical description, aerodynamic data in tabular or curve-fit form, blade frequencies and mode shapes, and pylon and shaft stiffness and inertia characteristics

4. Wing, fin/rudder, and elevator center-of-pressure areas, aerodynamic curve-fit constants, incidence angles, and coefficients to approximate interference effects

5. Auxiliary thrust location (if any), orientation, and level

6. Control linkages

7. Flight constants such as altitude, airspeed, and density and initial guesses for trim control positions and aircraft attitude

For maneuvers, the following additional data are required:

8. Weapon location and orientation

9. Stability and control augmentation system (SCAS) transfer function constants

10. Description of the maneuver

11. List of variables to be plotted as functions of time

The Myklestad program for calculating mode shapes and natural frequencies requires a complete description of the distribution of rotor blade properties, including

1. Twist

2. Weight

3. Beamwise, chordwise, and torsional stiffness

4. Shear center and cg location

5. Beamwise and chordwise moments of inertia

Although most of the inputs are easily understood, many are not nearly so easily obtained. Experience has shown that at least a week will be required to compile an operating deck if data are readily available. Estimation of parameters not available may require considerable engineering experience, supplementary computation, or refinement to obtain correlation with experimental data.

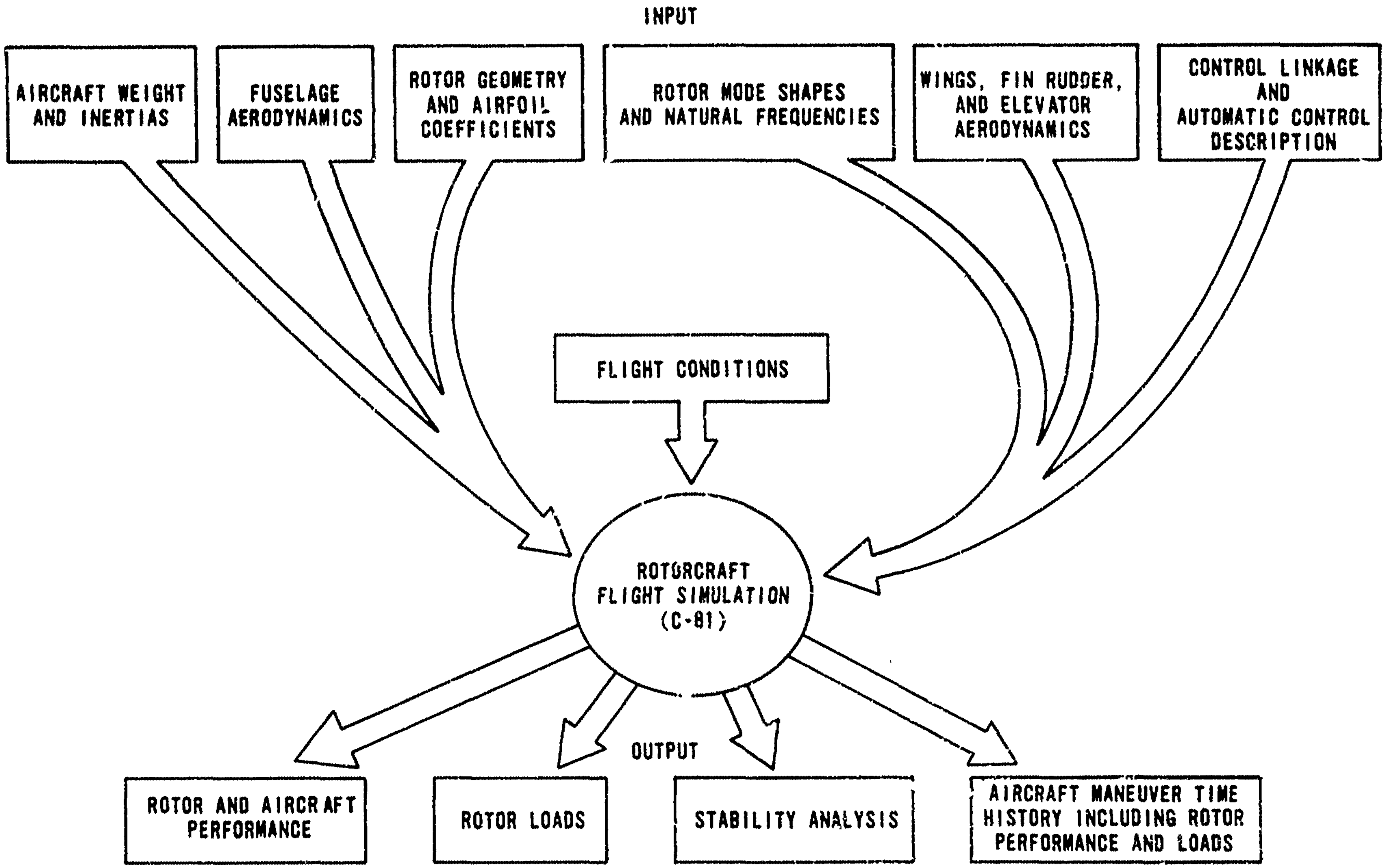

Figure 3. Input and Output of the Rotorcraft Flight Simulation.

PROGRAM USE

The analysis for the computer program consists of three major portions: trim, in which the control positions, aircraft attitude, and blade flapping angles necessary to achieve a stabilized flight condition are calculated; stability analysis, in which aircraft and rotor stability derivatives and roots of the aircraft characteristic equations are obtained; and maneuver, in which the response of the aircraft is computed for nonequilibrium flight conditions. The following subsections describe uses of the program in each of these major modes of operation.

TRIM

Trim values of control positions, rotor flapping angles, and aircraft attitude are computed for either level or climbing flight or for steady-state turns or steady "g" pull-ups. Aerodynamic forces and moments from the rotors, fuselage, and lifting surfaces are compared with components of the aircraft weight (or steady-state angular accelerations for steady-state maneuvers) for a given set of control positions and aircraft attitude. Simultaneously, rotor flapping moments and accelerations are compared to determine if they are consistent with the rotor blade root boundary conditions. If an equilibrium state does not result, the required changes in the independent variables are computed.

If it is assumed that for Z-force, Z = Z(CP, F/AC, LC, P, A1MR, B1MR, A1TR, B1TR, Θ, Φ)

where
- CP = collective pitch
- F/AC = fore-aft cyclic
- LC = lateral cyclic
- P = pedal
- A1MR = main rotor longitudinal flapping
- B1MR = main rotor lateral flapping
- A1TR = tail rotor longitudinal flapping
- B1TR = tail rotor lateral flapping
- Θ = fuselage pitch angle
- Φ = fuselage roll angle (or Ψ = yaw angle)

and that yaw angle is an input while roll angle is a variable, then

$$\Delta Z = \frac{\partial Z}{\partial CP}\Delta CP + \frac{\partial Z}{\partial F/AC}\Delta F/AC + \frac{\partial Z}{\partial LC}\Delta LC + \frac{\partial Z}{\partial P}\Delta P + \frac{\partial Z}{\partial A1MR}\Delta A1MR$$

$$+ \frac{\partial Z}{\partial B1MR}\Delta B1MR + \frac{\partial Z}{\partial A1TR}\Delta A1TR + \frac{\partial Z}{\partial B1TR}\Delta B1TR + \frac{\partial Z}{\partial \Theta}\Delta\Theta$$

$$+ \frac{\partial Z}{\partial \Phi}\Delta\Phi = -\text{ error in Z-force.}$$

When similar equations are written for the other aircraft forces and moments and the flapping moments for both rotors and are collected in matrix form, the following equation results:

$$\underset{\text{(Partial derivative matrix)}}{10 \times 10} \; \underset{\text{(Controls change matrix)}}{10 \times 1} = \underset{-\text{(Error matrix)}}{10 \times 1}$$

In the C-81 trim procedure, the error matrix is computed from the previous trim iteration; the partial derivative matrix is evaluated numerically, and this matrix equation is solved to find changes to the independent control variables that would produce an exact trim condition if the system were linear. Since it is not, more than one iteration is required; but 5 to 20 iterations are usually sufficient to obtain a force balance.

Repetition of this iterative process eventually provides values of the independent variables required for steady-state flight. Trim values of aircraft performance parameters and rotor loads are then printed out. A multiple case capability permits incremental changes in input parameters for efficient examination of the effects of speed, gross weight, rpm, etc. A sample of the trim output for the aeroelastic version of the program is shown in Figure 4.

This output suggests the following uses of the program:

1. Prediction of rotor performance and loads
2. Prediction of control positions
3. Prediction of speed-power polars
4. Prediction of aircraft attitude versus speed
5. Definition of required control range
6. Definition of cg limits and maximum gross weight for stable flight
7. Prediction of steady-state flight envelope considering rotor stall and loads, tail rotor and stabilizing surface sizes, and power available
8. Optimum rotor design
9. Analysis of lift sharing for compound helicopters
10. Prediction of increases in performance due to advanced airfoils
11. Evaluation of propulsive force requirements and effects of auxiliary propulsion
12. Prediction of aircraft turn and climb performance

13. Design of tail rotor and control surface sizes

14. Design of control couplings for best attitude versus speed

STABILITY AND CONTROL

A stability analysis is available for use at each trim condition and for user-specified times during a maneuver. Small-perturbation stabilility and control characteristics are predicted taking into account six fully coupled fuselage degrees of freedom plus pylon and rotor degrees of freedom. Characteristics for pitch attitude response to fore-aft cyclic, roll attitude response to lateral cyclic, and yaw angle rate response to pedal input are also calculated. A sample of the output from the stability analysis section of the program is shown in Figure 5.

Uses of the stability and control section of the program include:

1. Prediction of stability derivatives

2. Orientation and sizing of stabilizing surface

3. Design of automatic control system

4. Definition of aircraft stability limits

5. Prediction of control power

6. Analysis of control gearing design

7. Selection of optimal hub restraint

8. Prediction of control margin

9. Determination of effects of lift sharing on compound helicopter stability

10. Design of integrated control system

MANEUVER

In the maneuver section, aircraft response to nonequilibrium flight conditions is calculated. In this section, the program is a true digital flight simulator, solving a highly coupled and nonlinear set of equations describing the dynamics and aerodynamics of the aircraft to predict its time-variant behavior. Maneuvers of the greatest interest to most program users are movements of the controls, encounters with vertical or horizontal gusts, changes in engine torque or auxiliary thrust, weapon fire, and activation or deactivation of the automatic stability and control system. Any of the allowable maneuvers may be used separately or in combination.

The user should be forewarned that maneuvers can consume large quantities of central processing unit (CPU) time on a computer. Whereas determination of a trim condition generally requires only 3 or 4 minutes, simulation of a 3- or 4-second real-time maneuver may require 45 minutes of computer time on an IBM 360. Also, simulation of, say, a pull-up will usually involve running of the maneuver several times. Since flight path is not an input, the user must estimate the control motions required to produce the desired maneuver. The first case output is then used to refine the input for the second case, and so forth, until the desired maneuver is obtained. A "restart" feature in the newer versions of the program allows the user to start the maneuver for the second case at any real-time point calculated in the first case, thus reducing total computer time (and cost). A sample of the program maneuver output is shown in Figure 6.

Following are a few of the uses of the maneuver section of the Rotorcraft Flight Simulation:

1. Determine aircraft gust response
2. Determine maneuver loads and blade response
3. Study minimum distance to clear an obstacle
4. Study reaction of the aircraft to firing on-board weapons
5. Examine large-perturbation response to control inputs
6. Simulate autorotations
7. Determine thrust and power maneuver limits
8. Simulate tactical maneuvers
9. Determine total aircraft stability by examining time histories
10. Control surface sizing for improved maneuverability
11. Study methods for maximum deceleration

Reference 9 explains the use of the Rotorcraft Flight Simulation for aircraft evaluation.

BELL HELICOPTER COMPANY
ROTORCRAFT FLIGHT SIMULATION PROGRAM A3AJ72
COMPUTED 04/26/73

1 1 AH-1G SAMPLE TRIM CASE 100 KNOTS
CLEAN FUSELAGE MEDIUM GROSS WEIGHT
SIX ELASTIC MODES INCLUDING TORSION

HELICOPTER IS IN STABLE CONDITION.

		MAIN	TAIL			
ROTOR COLLECTIVE PITCH	(DEGREES)	14.321	2.548	WING ANGLE OF ATTACK	(DEGREES)	6.715
F/A CYCLIC PITCH	(DEGREES)	0.456	0.0	BODY Z-FORCE (+DOWN)	(LBS)	-333.337
LAT CYCLIC PITCH	(DEGREES)	-1.219	0.0	BODY X-FORCE (+FWD)	(LBS)	-72.288
F/A FLAPPING	(DEGREES)	3.276	1.592	ELEVATOR ANGLE OF ATTACK	(DEGREES)	-4.653
LAT FLAPPING	(DEGREES)	-0.033	0.024	BODY Z-FORCE (+DOWN)	(LBS)	100.209
THRUST	(LBS)	8482.417	208.805	BODY X-FORCE (+FWD)	(LBS)	11.303
H-FORCE	(LBS)	540.262	10.147	FIN ANGLE OF ATTACK	(DEGREES)	2.890
Y-FORCE	(LBS)	-155.183	3.189	BODY Y-FORCE (+RIGHT)	(LBS)	56.862
HORSEPOWER		460.796	13.566	BODY X-FORCE (+FWD)	(LBS)	-7.867
RPM		324.060	1656.599	HELICOPTER EULER ANGLE YAW	(DEGREES)	-1.000
MAST TILT ANGLE	(DEGREES)	0.0	0.0	PITCH	(DEGREES)	-5.793
BLADE INERTIA	(SLUG-FT-SQ)	1411.507	1.398	ROLL	(DEGREES)	-0.168
JET THRUST, LEFT SIDE	(LBS)	0.0		RATE OF CLIMB	(FT/SEC)	0.0
RIGHT SIDE	(LBS)	0.0		FORWARD SPEED	(KNOTS)	100.002
PCT CONTROL USED	COLLECTIVE	24.902		GROSS WEIGHT	(LBS)	8673.199
	F/A CYCLIC	50.577		ENGINE RPM		6600.000
	LAT CYCLIC	53.827		C.G. STATION LINE	(IN)	193.000
	PEDAL	33.522		WATER LINE	(IN)	71.000

PART 1 1 ITERATIONS 3.608 MINUTES ELAPSED COMPUTING TIME

Figure 4. Sample Trim Section Output.

ROTOR NUMBER 1 BEAM BENDING MOMENTS INCH-POUNDS

SINE COMPONENTS

STATION / HARMONIC	STEADY	1/REV	2/REV	3/REV	4/REV	5/REV	6/REV	7/REV	8/REV
1	0.0	-354.4	22.7	25.1	1.1	0.2	0.0	0.0	0.0
2	0.0	-1049.2	61.5	68.9	3.0	0.7	0.2	0.1	0.1
3	0.0	-1658.7	96.4	109.3	4.7	1.1	0.3	0.1	0.1
4	0.0	-2334.3	136.3	153.9	6.5	1.5	0.3	0.2	0.2
5	0.0	-3124.0	183.3	205.9	8.7	2.0	0.4	0.2	0.2
6	0.0	-3913.1	230.8	257.8	10.9	2.4	0.5	0.3	0.2
7	0.0	-4256.8	249.7	281.7	11.5	2.6	0.6	0.3	0.3
8	0.0	-3885.6	225.0	260.1	10.3	2.6	0.6	0.4	0.3
9	0.0	-3303.7	185.7	224.9	8.3	2.4	0.7	0.4	0.3
10	0.0	-3057.2	164.4	209.9	7.2	2.3	0.6	0.4	0.3
11	0.0	-3104.5	165.9	211.9	6.8	2.0	0.5	0.3	0.2
12	0.0	-3313.0	177.7	220.8	6.4	1.5	0.1	0.0	0.0
13	0.0	-3624.0	198.7	231.2	5.7	0.4	-0.7	-0.5	-0.4
14	0.0	-4062.5	232.5	240.5	4.3	-1.8	-2.1	-1.4	-1.2
15	0.0	-4624.4	281.2	243.6	1.7	-5.5	-4.6	-3.0	-2.6
16	0.0	-5100.4	335.4	222.0	-3.1	-11.6	-8.4	-5.5	-4.5
17	0.0	-4645.4	347.0	124.0	-12.1	-20.0	-13.5	-8.7	-7.6
18	0.0	-1023.0	192.2	-183.1	-29.7	-30.9	-19.2	-12.3	-10.8
19	0.0	-5740.3	16.0	409.3	-7.0	5.4	1.8	1.2	1.0
20	0.0	-560.2	-440.2	59.5	-37.8	1.0	0.3	0.4	0.3

COSINE COMPONENTS

STATION / HARMONIC	STEADY	1/REV	2/REV	3/REV	4/REV	5/REV	6/REV	7/REV	8/REV
1	-275.3	41.1	17.6	[illegible]	0.3	-0.0	0.1	0.1	0.0
2	-750.2	109.5	46.3	62.1	0.8	0.0	0.2	0.2	0.1
3	-1166.6	165.2	75.4	98.4	1.4	0.1	0.4	0.3	0.3
4	-1659.5	159.2	104.9	135.4	2.0	0.1	0.6	0.4	0.3
5	-2235.0	265.3	142.4	184.9	2.6	0.2	0.7	0.5	0.4
6	-2815.5	376.2	181.0	231.3	3.4	0.2	0.8	0.6	0.5
7	-3058.2	405.9	194.5	252.1	3.5	0.3	1.0	0.7	0.6
8	-2733.1	340.7	174.6	231.7	3.8	0.4	1.1	0.8	0.7
9	-2285.1	255.5	136.5	199.0	3.7	0.6	1.1	0.8	0.8
10	-2088.7	217.1	114.5	184.7	3.6	0.7	1.1	0.8	0.7
11	-2205.3	317.7	95.2	186.1	3.6	0.5	0.9	0.7	0.6
12	-2534.9	395.4	68.2	194.5	3.4	0.1	0.5	0.3	0.2
13	-3104.9	812.4	22.8	204.7	2.5	-0.9	-0.3	-0.6	-0.6
14	-4057.4	1512.2	-57.0	215.4	1.5	-2.7	-1.9	-2.2	-2.2
15	-5565.5	2843.2	-200.4	222.5	-1.1	-5.9	-4.7	-4.9	-4.9
16	-7573.5	4624.4	-422.9	210.3	-5.5	-10.7	-9.1	-9.3	-9.0
17	-9492.3	6781.7	-765.0	131.5	-12.0	-17.1	-15.0	-15.0	-14.5
18	-9510.1	8724.0	-1261.6	-136.1	-20.8	-23.7	-21.8	-21.3	-20.6
19	-7358.7	414.7	-1865.8	354.3	6.9	2.4	2.5	2.4	2.3
20	-9366.0	369.5	-4205.7	39.2	1.4	1.2	0.2	0.8	0.9

Figure 4. Continued.

ROTOR NUMBER 1 CHRD BENDING MOMENTS INCH-POUNDS

SINE COMPONENTS

STATION / HARMONIC	STEADY	1/REV	2/REV	3/REV	4/REV	5/REV	6/REV	7/REV	8/REV
1	0.0	441.9	2.3	-40.8	-1.3	-1.7	-0.9	-0.6	-0.5
2	0.0	1654.2	5.3	-151.9	-5.0	-6.2	-3.4	-2.2	-1.9
3	0.0	3290.4	5.8	-301.1	-10.1	-12.2	-6.6	-4.3	-3.7
4	0.0	5113.6	3.4	-467.3	-15.5	-15.9	-10.3	-6.6	-5.8
5	0.0	7130.5	-2.0	-649.9	-22.7	-26.2	-14.2	-9.2	-8.0
6	0.0	9357.0	-12.9	-851.4	-29.4	-34.2	-18.5	-12.0	-10.4
7	0.0	11852.5	-31.9	-1077.4	-37.9	-43.2	-23.4	-15.1	-13.2
8	0.0	14626.9	-60.5	-1329.1	-47.6	-53.3	-28.9	-18.6	-16.3
9	0.0	17585.9	-95.1	-1599.6	-58.4	-64.2	-34.8	-22.5	-19.6
10	0.0	20667.0	-132.7	-1882.3	-69.5	-75.7	-41.1	-26.5	-23.1
11	0.0	23843.1	-174.4	-2175.5	-81.9	-87.8	-47.7	-30.8	-26.9
12	0.0	27124.5	-218.6	-2480.2	-94.7	-100.5	-54.6	-35.2	-30.6
13	0.0	30485.3	-267.1	-2794.6	-108.1	-113.7	-61.9	-39.9	-34.8
14	0.0	33925.9	-318.6	-3115.5	-122.2	-127.6	-69.5	-44.8	-39.1
15	0.0	37439.3	-373.4	-3452.0	-137.0	-142.0	-77.5	-49.9	-43.6
16	0.0	41005.9	-432.1	-3793.6	-152.4	-157.0	-85.7	-55.3	-48.3
17	0.0	44535.2	-495.3	-4136.9	-168.5	-172.5	-94.3	-60.8	-53.1
18	0.0	47811.1	-570.1	-4472.7	-156.0	-185.8	-103.5	-66.7	-58.3
19	0.0	50914.4	-671.9	-4845.1	-213.0	-211.2	-116.5	-75.1	-65.6
20	0.0	55859.9	-856.6	-5327.6	-240.5	-233.1	-128.7	-82.9	-72.4

COSINE COMPONENTS

STATION / HARMONIC	STEADY	1/REV	2/REV	3/REV	4/REV	5/REV	6/REV	7/REV	8/REV
1	-96.5	328.3	4.2	-33.0	-1.2	-1.1	-1.1	-1.0	-1.0
2	-306.1	1248.2	15.0	-130.5	-4.6	-4.1	-3.9	-3.8	-3.7
3	-343.3	2402.3	26.6	-258.6	-9.1	-8.0	-7.7	-7.5	-7.2
4	-766.9	3695.6	37.8	-401.8	-14.1	-12.3	-11.9	-11.6	-11.1
5	-989.0	5079.5	44.9	-559.0	-19.6	-17.0	-16.5	-16.0	-15.4
6	-1156.9	6684.9	52.9	-732.4	-25.7	-22.2	-21.6	-20.9	-20.1
7	-1271.3	8395.0	54.2	-926.9	-32.6	-28.1	-27.3	-26.4	-25.4
8	-1290.5	10417.4	55.6	-1143.6	-40.4	-34.6	-33.7	-32.5	-31.3
9	-1277.3	12510.6	52.0	-1376.1	-48.9	-41.7	-40.6	-39.2	-37.8
10	-1266.5	14735.0	43.5	-1615.9	-58.0	-49.2	-47.9	-46.3	-44.6
11	-1196.9	17203.2	41.6	-1870.7	-67.5	-57.2	-55.7	-53.8	-51.3
12	-1143.3	19695.3	32.6	-2132.0	-77.5	-65.5	-63.8	-61.6	-59.3
13	-1037.0	22431.5	28.0	-2401.5	-88.0	-74.3	-72.3	-69.8	-67.2
14	-918.5	25163.4	21.9	-2675.7	-99.0	-83.4	-81.2	-78.3	-75.4
15	-783.5	28147.4	15.1	-2964.1	-110.5	-93.0	-90.5	-87.3	-84.0
16	-611.5	31291.5	10.3	-3256.0	-122.5	-103.1	-100.2	-96.7	-93.0
17	-405.3	34422.8	2.8	-3549.6	-135.0	-113.5	-110.2	-106.3	-102.3
18	-58.9	38010.2	0.9	-3833.1	-148.4	-124.7	-121.0	-116.7	-112.3
19	-1324.7	43304.0	-437.7	-4145.7	-166.3	-140.5	-136.1	-131.2	-126.3
20	-233.3	47927.3	-615.0	-4557.2	-194.7	-155.2	-150.4	-144.9	-139.5

Figure 4. Continued.

ROTOR NUMBER 1 TORS BENDING MOMENTS INCH-POUNDS

SINE COMPONENTS

STATION / HARMONIC	STEADY	1/REV	2/REV	3/REV	4/REV	5/REV	6/REV	7/REV	8/REV
1	0.0	-17.2	1.3	7.1	-1.0	-0.1	-0.0	-0.0	-0.0
2	0.0	-34.3	2.6	14.2	-2.0	-0.1	-0.1	-0.0	-0.0
3	0.0	-51.3	3.8	21.1	-3.0	-0.2	-0.1	-0.1	-0.0
4	0.0	-65.4	5.1	27.9	-3.9	-0.2	-0.1	-0.1	-0.1
5	0.0	-84.1	6.3	33.9	-4.7	-0.3	-0.2	-0.1	-0.1
6	0.0	-94.4	7.0	37.8	-5.3	-0.3	-0.2	-0.1	-0.1
7	0.0	-103.1	7.7	41.1	-5.7	-0.3	-0.2	-0.1	-0.1
8	0.0	-111.1	8.5	44.0	-6.1	-0.3	-0.2	-0.1	-0.1
9	0.0	-119.3	9.8	46.4	-6.4	-0.4	-0.2	-0.1	-0.1
10	0.0	-126.7	9.4	48.7	-6.7	-0.4	-0.2	-0.1	-0.1
11	0.0	-135.1	10.1	51.1	-7.0	-0.4	-0.3	-0.2	-0.1
12	0.0	-144.2	10.6	53.1	-7.2	-0.4	-0.3	-0.2	-0.1
13	0.0	-151.2	11.1	54.7	-7.4	-0.4	-0.3	-0.2	-0.1
14	0.0	-157.5	11.5	56.1	-7.5	-0.4	-0.3	-0.2	-0.1
15	0.0	-162.3	11.9	57.2	-7.7	-0.4	-0.3	-0.2	-0.1
16	0.0	-166.0	12.2	58.0	-7.8	-0.4	-0.3	-0.2	-0.1
17	0.0	-169.2	12.4	58.7	-7.8	-0.4	-0.3	-0.2	-0.1
18	0.0	-171.4	12.5	59.2	-7.9	-0.4	-0.3	-0.2	-0.1
19	0.0	-173.2	12.6	59.6	-7.9	-0.4	-0.3	-0.2	-0.1
20	0.0	-173.7	12.7	59.7	-8.0	-0.4	-0.3	-0.2	-0.1

COSINE COMPONENTS

STATION / HARMONIC	STEADY	1/REV	2/REV	3/REV	4/REV	5/REV	6/REV	7/REV	8/REV
1	-19.0	9.5	17.8	2.5	1.0	0.3	0.1	0.1	0.1
2	-37.5	18.6	35.5	5.0	2.0	0.5	0.3	0.2	0.1
3	-55.4	27.9	52.8	7.4	3.0	0.8	0.4	0.3	0.2
4	-75.0	37.0	69.5	9.8	4.0	1.0	0.6	0.4	0.3
5	-91.9	44.6	84.7	12.0	4.6	1.2	0.7	0.4	0.3
6	-103.5	47.9	94.3	13.4	5.4	1.3	0.8	0.5	0.4
7	-113.0	50.0	102.3	14.5	5.9	1.5	0.8	0.5	0.4
8	-121.3	51.6	109.2	15.6	6.3	1.6	0.9	0.6	0.4
9	-130.1	52.5	115.1	15.5	6.5	1.6	0.9	0.6	0.4
10	-139.4	53.2	120.4	17.4	6.9	1.7	1.0	0.6	0.5
11	-147.7	54.0	125.9	18.4	7.2	1.8	1.0	0.7	0.5
12	-155.5	55.1	130.5	19.2	7.5	1.9	1.1	0.7	0.5
13	-162.4	56.9	133.9	19.9	7.7	1.9	1.1	0.7	0.5
14	-169.5	57.2	137.0	20.5	7.9	1.9	1.1	0.7	0.5
15	-173.4	57.1	139.3	21.0	8.0	2.0	1.1	0.7	0.5
16	-177.0	55.7	141.1	21.4	8.1	2.0	1.1	0.7	0.5
17	-180.2	54.3	142.5	21.7	8.2	2.0	1.2	0.7	0.5
18	-182.7	53.2	143.7	21.9	8.2	2.0	1.2	0.7	0.5
19	-184.3	52.4	144.5	22.1	8.3	2.0	1.2	0.8	0.5
20	-184.9	52.1	144.8	22.1	8.3	2.1	1.2	0.8	0.5

Figure 4. Continued.

ROTOR NUMBER 1SUMMARY INCH POUNDS

BEAM BENDING MOMENT

STATION	OSCILLATORY	MAXIMUM	AZ	MINIMUM	AZ
1	411.	120.	260.	-702.	90.
2	1122.	331.	260.	-1913.	90.
3	1775.	542.	260.	-3008.	90.
4	2303.	757.	250.	-4250.	90.
5	3347.	991.	260.	-5703.	90.
6	4159.	1215.	250.	-7162.	90.
7	4538.	1330.	250.	-7785.	90.
8	4155.	1283.	260.	-7048.	90.
9	3549.	1132.	260.	-5945.	90.
10	3285.	1104.	250.	-5465.	90.
11	3325.	1037.	260.	-5612.	90.
12	3537.	941.	260.	-6132.	90.
13	3952.	729.	270.	-6996.	100.
14	4374.	304.	270.	-8443.	100.
15	5292.	-320.	290.	-10903.	120.
16	5679.	-1149.	300.	-14506.	140.
17	5143.	-1964.	320.	-18250.	150.
18	5537.	-1827.	340.	-19501.	170.
19	6190.	663.	270.	-11698.	80.
20	4720.	-4539.	270.	-13960.	180.

CHORD BENDING MOMENT

STATION	OSCILLATORY	MAXIMUM	AZ	MINIMUM	AZ
1	592.	486.	60.	-678.	240.
2	2197.	1881.	60.	-2493.	240.
3	4309.	3763.	60.	-4855.	240.
4	6676.	5903.	60.	-7450.	240.
5	9272.	8272.	60.	-10272.	240.
6	12176.	10999.	60.	-13353.	240.
7	15386.	14083.	60.	-16689.	240.
8	19016.	17675.	60.	-20357.	240.
9	22859.	21510.	60.	-24209.	240.
10	26880.	25520.	60.	-28239.	240.
11	31146.	29799.	60.	-32433.	240.
12	35465.	34175.	60.	-36754.	240.
13	40013.	33797.	60.	-41226.	240.
14	44633.	43505.	60.	-45760.	240.
15	49451.	48424.	60.	-50477.	240.
16	54703.	53510.	60.	-55296.	240.
17	59316.	58589.	60.	-60043.	240.
18	64229.	63796.	60.	-64662.	240.
19	69873.	68325.	60.	-71422.	240.
20	76877.	76366.	60.	-77387.	240.

TORSIONAL BENDING MOMENT

STATION	OSCILLATORY	MAXIMUM	AZ	MINIMUM	AZ
1	35.	12.	0.	-60.	90.
2	72.	24.	0.	-120.	90.
3	109.	36.	0.	-179.	90.
4	142.	48.	0.	-238.	90.
5	174.	57.	0.	-290.	90.
6	193.	61.	0.	-325.	90.
7	209.	63.	0.	-354.	90.
8	222.	64.	0.	-381.	90.
9	234.	64.	0.	-405.	90.
10	246.	63.	0.	-428.	90.
11	259.	63.	0.	-454.	90.
12	269.	62.	0.	-476.	90.
13	275.	60.	0.	-495.	90.
14	285.	58.	0.	-512.	90.
15	291.	56.	0.	-525.	90.
16	294.	54.	0.	-535.	90.
17	297.	51.	0.	-543.	90.
18	299.	49.	0.	-550.	90.
19	301.	47.	0.	-554.	90.
20	301.	47.	0.	-556.	90.

Figure 4. Concluded.

CONTROL PARTIAL DERIVATIVE MATRICES

POUNDS/INCH OR FOOT-POUNDS/INCH

	COLLECTIVE	F/A CYCLIC	LAT CYCLIC	PEDAL
X-FORCE	-420.1	438.5	-22.00	-16.84
Y-FORCE	-55.75	55.70	229.1	316.0
Z-FORCE	-3699.	1171.	-36.71	12.69
YAW MOM	1818.	1180.	-247.0	-3689.
PITCH MOM	1473.	-2851.	131.5	411.4
ROLL MOM	-380.7	376.5	1548.	1294.
M.R. F/A FLAP MOM	11.02	10.89	7.184	-162.1
M.R. LAT FLAP MOM	-6.182	-6.097	-4.021	54.12
T.R. F/A FLAP MOM	.0	.0	.0	.0
T.R. LAT FLAP MOM	.0	.0	.0	.0
M.R. F/A PYLON MOM	13.96	-17.43	-1.926	.1963E-01
M.R. LAT PYLON MOM	.9465	.1557	-9.053	.6226E-02
T.R. F/A PYLON MOM	.0	.0	.0	.5504E-03
T.R. LAT PYLON MOM	.0	.0	.0	-.4589E-03

FT/SEC**2 OR RAD/SEC**2 PER INCH

	COLLECTIVE	F/A CYCLIC	LAT CYCLIC	PEDAL
X-FORCE	-1.558	1.526	-.8159E-01	-.6245E-01
Y-FORCE	-.2069	.2066	.8495	1.172
Z-FORCE	-13.72	4.344	-.1362	.4706E-01
YAW MOM	.1614	.1049	-.2192E-01	-.7714
PITCH MOM	.1123	-.2174	.1003E-01	.3136E-01
ROLL MOM	-.1339	.1324	.5443	.4552
M.R. F/A FLAP MOM	.7809E-02	.7716E-02	.5089E-02	-.1148
M.R. LAT FLAP MOM	-.4379E-02	-.4319E-02	-.2848E-02	.3834E-01
T.R. F/A FLAP MOM	.0	.0	.0	.0
T.R. LAT FLAP MOM	.0	.0	.0	.0
M.R. F/A PYLON MOM	.1045E+20	.1182E+09	-136.3	1.063
M.R. LAT PYLON MOM	.3195E+07	-.1344E-50	-.8761	.4801E-47
T.R. F/A PYLON MOM	.1679E-44	.9871E-52	-2.035	-8.391
T.R. LAT PYLON MOM	.0454E-78	-60.25	-136.3	.1471E-37

CONVENTIONAL FIXED WING NON-DIMENSIONAL DERIVATIVES

	COLLECTIVE	F/A CYCLIC	LAT CYCLIC	PEDAL
X-FORCE	-.5129	.5352	-.2685E-01	-.2055E-01
Y-FORCE	-.6906E-01	.6799E-01	.2797	.3858
Z-FORCE	-4.515	1.430	-.4482E-01	.1549E-01
YAW MOM	.2129	.1382	-.2891E-01	-1.017
PITCH MOM	.5744	-1.305	.6021E-01	.1883
ROLL MOM	-.4459E-01	.4403E-01	.1812	.1515
M.R. F/A FLAP MOM	.5047E-02	.4987E-02	.3289E-02	-.7420E-01
M.R. LAT FLAP MOM	-.7238E-03	-.7139E-03	-.4708E-03	.6337E-02
T.R. F/A FLAP MOM	.0	.0	.0	.0
T.R. LAT FLAP MOM	.0	.0	.0	.0
M.R. F/A PYLON MOM	.6393E-02	-.7980E-02	-.8818E-03	.8989E-05
M.R. LAT PYLON MOM	.1108E-03	.1823E-04	-.1060E-02	.7289E-06
T.R. F/A PYLON MOM	.0	.0	.0	.2520E-06
T.R. LAT PYLON MOM	.0	.0	.0	-.5373E-07

Figure 5. Sample Stability Section Output.

ROTOR PARTIAL DERIVATIVE MATRICES

MAIN ROTOR

	U	W	Q	V	P	R
THRUST	19.228	178.95	159.05	2.3680	270.23	-534.53
H-FORCE	5.3495	14.945	-831.53	-.25117	236.92	-30.532
F/A FLAPPING	.93372E-03	.67774E-03	-.12235	.31948E-04	.22910E-01	.0
Y-FORCE	-1.3950	-3.3155	-121.74	-3.8289	-783.33	10.589
TORQUE	-25.281	-175.62	9215.3	-1.9742	-3569.8	-588.05
LAT FLAPPING	-.69538E-04	.29582E-05	-.19732E-01	-.40155E-03	-.11526	.0

TAIL ROTOR

	U	W	Q	V	P	R
THRUST	.44984	-.13779	-7.4930	-7.9059	-4.8453	277.47
H-FORCE	.66390E-01	.10245E-01	-.12487	-.31088	.81148	9.1173
F/A FLAPPING	.0	.0	.0	-.42751E-03	.16154E-01	.0
Y-FORCE	.27145E-01	-.37892E-01	-1.1937	-.18860	-6.0507	6.3010
TORQUE	.10755	-.62492E-01	-3.2382	.65839	9.7034	-17.209
LAT FLAPPING	.0	.0	.0	-.30203E-03	-.33225E-01	.0

MASS MATRIX

	U DOT	W DOT	Q DOT	V DOT	P DOT	R DOT
X-FORCE	269.60	.0	.0	.0	.0	.0
Z-FORCE	.0	269.70	.0	.0	.0	.0
PITCH MOMENT	.0	1.5551	13114.	.0	.0	.0
Y-FORCE	.0	.0	.0	269.60	.0	.0
ROLL MOMENT	.0	.0	.0	.0	2843.0	-957.00
YAW MOMENT	.0	.0	.0	.0	-957.00	11264.

Figure 5. Continued.

DAMPING MATRIX

	U	W	Q	V	P	R
X-FORCE	9.9318	18.122	-5401.1	.0	.0	.0
Z-FORCE	24.291	202.13	-45232.	.0	.0	.0
PITCH MOMENT	-17.195	37.309	7799.0	.0	.0	.0
Y-FORCE	.0	.0	.0	41.233	5384.0	45061.
ROLL MOMENT	.0	.0	.0	-11.410	5309.3	-1324.9
YAW MOMENT	.0	.0	.0	-208.60	2932.3	12156.

STIFFNESS MATRIX

	X	Z	THETA	Y	PHI	PSI
X-FORCE	.0	.0	8628.9	.0	.0	.0
Z-FORCE	.0	.0	-875.47	.0	.0	.0
PITCH MOMENT	.0	.0	.0	.0	.0	.0
Y-FORCE	.0	.0	.0	.0	-8628.9	875.47
ROLL MOMENT	.0	.0	.0	.0	.0	.0
YAW MOMENT	.0	.0	.0	.0	.0	.0

Figure 5. Continued.

NORMALIZED WRT THETA

	MAGN PHASE	MAGN PHASE	MAGN PHASE	MAGN PHASE	MAGN PHASE	MAGN PHASE	MAGN PHASE	MAGN PHASE
JSELAGE								
U	.3595 .0	.9582E-01 .0	.1925 53.09	.9069 94.11	.3505 44.52	.0 .0	.0 .0	.0 .0
W	.1544 .0	1.527 180.0	.6095 -23.37	.1705 65.25	1.449 53.66	.0 .0	.0 .0	.0 .0
THETA	1.000 .0	1.000 .0	1.000 .0	1.000 .0	1.000 .0	.0 .0	.0 .0	.0 .0
BETA	.2164E+22 180.0	.6023E+24 .0	.7587E+24 -11.92	.1363E-23 163.4	.1206E-23 49.49	.0 .0	.0 .0	.0 .0
PHI	.4197E+23 180.0	.2946E+25 180.0	.3419E+24 175.0	.2546E-22 155.3	.4119E-23 -107.2	.0 .0	.0 .0	.0 .0
PSI	.1073E+24 180.0	.3547E+23 .0	.7007E+24 160.9	.4355E-22 121.9	.5137E-23 -137.3	.0 .0	.0 .0	.0 .0

Figure 5. Continued.

N O R M A L I Z E D   W R T   P H I

	MAGN PHASE	MAGN PHASE	MAGN PHASE	MAGN PHASE	MAGN PHASE	MAGN PHASE	MAGN PHASE	MAGN PHASE
JSELAGE								
U	.1360E-22	.3231E-25	.5337E-24	.3966E+23	.3753E+23	.0	.0	.0
	180.0	180.0	-121.9	-62.15	151.7	.0	.0	.0
W	.3734E-23	.5140E-24	.1783E-23	.7268E+22	.3516E+24	.0	.0	.0
	180.0	.0	161.7	-91.02	160.9	.0	.0	.0
THETA	.2389E-22	.3372E-24	.2925E-23	.4263E+23	.2429E+24	.0	.0	.0
	180.0	180.0	-175.0	-155.3	107.2	.0	.0	.0
BETA	.4929E-01	.2334	2.219	.6236E-01	.2930	.0	.0	.0
	.0	180.0	173.1	9.095	155.7	.0	.0	.0
PHI	1.000	1.000	1.000	1.000	1.000	.0	.0	.0
	.0	.0	.0	.0	.0	.0	.0	.0
PSI	2.562	.1196E-01	2.049	1.356	1.490	.0	.0	.0
	.0	180.0	-14.13	-34.39	-30.12	.0	.0	.0

Figure 5. Continued.

FREQUENCY RESPONSE

THETA/FORE-AND-AFT CYCLIC GAIN = 0.21789E+00 STATIC GAIN = 0.86577E-01

ROOTS				ROOTS			
REAL	IMAG	TAU	DAMP	REAL	IMAG	TAU	DAMP
.99103E-01	.0	.0	-20.365	-1.7755	.0	.0	.56289
-.75296	1.7444	.27707	.41697	-.81232	.0	.0	1.2310
-.19825E-01	.0	.0	50.442				

PHI/LATERAL CYCLIC GAIN = -0.55275E+00 STATIC GAIN = 0.10796E+00

ROOTS				ROOTS			
REAL	IMAG	TAU	DAMP	REAL	IMAG	TAU	DAMP
-.18481E-01	.0	.0	54.110	-.61283	1.7151	.30053	.36834
-.50111E-02	.21332	21.963	.22012	-.59500	.63565	1.1273	1.5669

PSI/PEDAL GAIN = 0.75426E+00 STATIC GAIN = 0.12051E+01

ROOTS				ROOTS			
REAL	IMAG	TAU	DAMP	REAL	IMAG	TAU	DAMP
-1.7436	.0	.0	.57354	.34235	.0	.0	-2.9210
-.80395	.0	.0	1.1856	-.50111E-02	.21332	21.963	.22012
-.59500	.63565	1.1273	1.5669				

Figure 5. Concluded.

```
9.100   SECONDS MANEUVER TIME          6.783   MINUTES ELAPSED COMPUTING TIME          LB,FT,DEG,SEC UNITS

                                        MAIN ROTOR SHAFT REFERENCE

AERO. FORCES            SHEAR FORCES              FROM       COLLEC F/A CYC LAT CYC        U  167.891
H-FORCE     -59.250         X      -525.540       CONTROLS   14.321   0.074   -1.219       V    3.027      H.TILT     0.0
Y-FORCE    -505.555         Y      -551.219       OTHER       0.0     0.0      0.0         W  -17.049      X HUB      0.0
THRUST     9910.789         Z    -23305.070       TOTAL      14.321   0.074   -1.219   V IND    9.978      Y HUB      0.0

TORQUE     8553.103     AZIMUTH       194.997     MAST WIND-UP          0.0       RPM          324.060          A1     2.917
HP          515.010     BETA HUB(1)     3.052     WIND-UP RATE          0.0       FLAP.LIM.     20.000          B1     1.641

                                        TAIL ROTOR SHAFT REFERENCE

AERO. FORCES            SHEAR FORCES              FROM       COLLEC F/A CYC LAT CYC        U  167.899
H-FORCE      11.231         X        11.231       CONTROLS    2.792   0.0      0.0         V  -17.049      H.TILT     0.0
Y-FORCE       3.547         Y        -5.547       OTHER       0.0     0.0      0.0         W   -2.471      X HUB      0.0
THRUST      224.540         Z       223.540       TOTAL       2.792   0.0      0.0     V IND    6.550      Y HUB      0.0

TORQUE       44.502     AZIMUTH       275.842     MAST WIND-UP          0.0       RPM         1556.597          A1     1.734
HP           14.757     BETA HUB(1)     0.404     WIND-UP RATE          0.0       FLAP.LIM.     20.000          B1     0.019

                                        FUSELAGE REFERENCE
                                                                                  EULER ANGLES FROM GROUND
                 U          V          W          P          Q          R       ORBWT                  PSI       THETA       PHI
ACCEL.       -0.555     -0.181     -3.512    -17.904      1.524      0.932       0.0    VELOCITY     -0.116      0.006      0.170
VELOCITY    167.492      3.307    -17.049      0.159      0.006     -0.115       0.0    LOCATION     -1.002     -5.789     -0.160

CONTROLS (PCT)
COL STK.     24.93                L.WING     R.WING      ELE      FIN/RUD    C.G. LOC (IN)               GUST (CG)        G-S
F/A STK.     49.15     ANG.ATK     6.522      6.522     -5.343     2.757     STA. LINE  193.00      FWD      0.0         -0.11
LAT STK.     53.93     CL          0.401      0.401     -0.261     0.171     B. LINE      0.0       LAT      0.0          0.01
PEDAL        54.49     CD          0.034      0.034      0.022     0.011     W. LINE     71.00      VERT     0.0          1.10

              JET THRUST                   FUSELAGE AERO.                 FLIGHT PATH ANGLES
              RIGHT/CENTER      0.0        ATK.YAW      -1.03             HEADING          0.00
              LEFT              0.0        ATK.PITCH    -5.80             CLIMB            0.01

              GROUND REFERENCE                                                              ENGINE
                 X            Y           Z                              SPEED (KNOTS)
VELOCITY     159.782        0.007      -0.035    DISTANCE       16.9    AIR    100.00    TORQUE       5390.5    TOTAL HP RQD.        530.0
LOCATION      15.925        0.000   -5000.000    ALTITUDE     5000.0    GND.   100.00    SHAFT HP      530.0    ROTOR BRAKE TORQ.      0.0

                                        FORCE AND MOMENT SUMMARY

                TOTAL     R.WING     L.WING       ELE        FIN       FUS   JETS+GUN       M.R.       T.R.      W/GMR        QTR

X-FORCE         -59.2      -35.5      -35.5      13.9       -7.8    -249.5      0.0     -539.3      -11.2      874.8
Y-FORCE        -115.4                                       54.4     -71.9      0.0     -303.7      228.6      -24.2
Z-FORCE        -497.5     -151.9     -151.9     115.4                93.4      0.0    -9915.0        3.6     8625.9
ROLL           -904.0     -525.3      525.3       0.0       59.0     215.2      0.0    -2065.4      595.2      -11.9       -0.0
PITCH           394.9      -13.1      -13.1    1993.0        8.4    -619.7      0.0    -1150.8      143.9      -44.1       44.5
YAW             492.3      115.4     -115.4       0.0    -1396.8    -403.3      0.0      177.1    -6257.9     8363.1       -0.0
```

Figure 6. Sample Maneuver Section Output.

**** MAIN ROTOR ****

VARIABLE	BLADE 1	BLADE 2	BLADE 3	BLADE 4	BLADE 5	BLADE 6	BLADE 7
AZIMUTH	194.999	14.999	0.0	0.0	0.0	0.0	0.0
GEN.COORD.MODE 1	1.245	-1.245	0.0	0.0	0.0	0.0	0.0
GEN.COORD.MODE 2	-0.028	0.026	0.0	0.0	0.0	0.0	0.0
GEN.COORD.MODE 3	0.003	-0.003	0.0	0.0	0.0	0.0	0.0
GEN.COORD.MODE 4	-0.279	-0.279	0.0	0.0	0.0	0.0	0.0
GEN.COORD.MODE 5	-0.030	-0.030	0.0	0.0	0.0	0.0	0.0
GEN.COORD.MODE 6	0.000	0.000	0.0	0.0	0.0	0.0	0.0
TIP DEFL.OUT-OF-PLANE	0.935	-1.554	0.0	0.0	0.0	0.0	0.0
TIP DEFL.INPLANE	-0.036	0.022	0.0	0.0	0.0	0.0	0.0
TIP TWIST DEFL.	-0.249	0.283	0.0	0.0	0.0	0.0	0.0
VERTICAL SHEAR AT HUB	-5059.059	-17974.344	0.0	0.0	0.0	0.0	0.0
INPLANE SHEAR AT HUB	-185.789	529.132	0.0	0.0	0.0	0.0	0.0
LOADS AT R = 0.0 IN							
BEAM BENDING MOMENT	-13079.910	-12531.453	0.0	0.0	0.0	0.0	0.0
CHORD BENDING MOMENT	-48319.719	48101.910	0.0	0.0	0.0	0.0	0.0
TORSIONAL MOMENT	-111.683	53.245	0.0	0.0	0.0	0.0	0.0

Figure 6. Continued.

```
                         BELL HELICOPTER COMPANY
              ROTORCRAFT FLIGHT SIMULATION PROGRAM AGAJ7204
                           COMPUTED  05/02/73

        3            0          AH-1G SAMPLE MANEUVER     100 KNOTS
                  CLEAN FUSELAGE  MEDIUM GROSS WEIGHT
                  SIX ELASTIC MODES INCLUDING TORSION
                                               SYMBOL 1 = ROTOR 1, AZIMUTH LOCATION, BLADE 1, DEG
                                               SYMBOL 2 =  AIR SPEED, KTS
                                               SYMBOL 4 =  Z-COMP 3-8, BODY AXES
SCALE   1   FROM    0.0     TO   200.000,  1 INCH =   20.000     3 FOR 1 + 2      ON SAME PRINT POS.
SCALE   2   FROM   95.000   TO   104.000,  1 INCH =    0.900     5 FOR 1 + 4      ON SAME PRINT POS.
SCALE   4   FROM    0.0     TO     2.000,  1 INCH =    0.200     6 FOR 2 + 4      ON SAME PRINT POS.
                                                                 7 FOR 1 + 2 + 4 ON SAME PRINT POS.
```

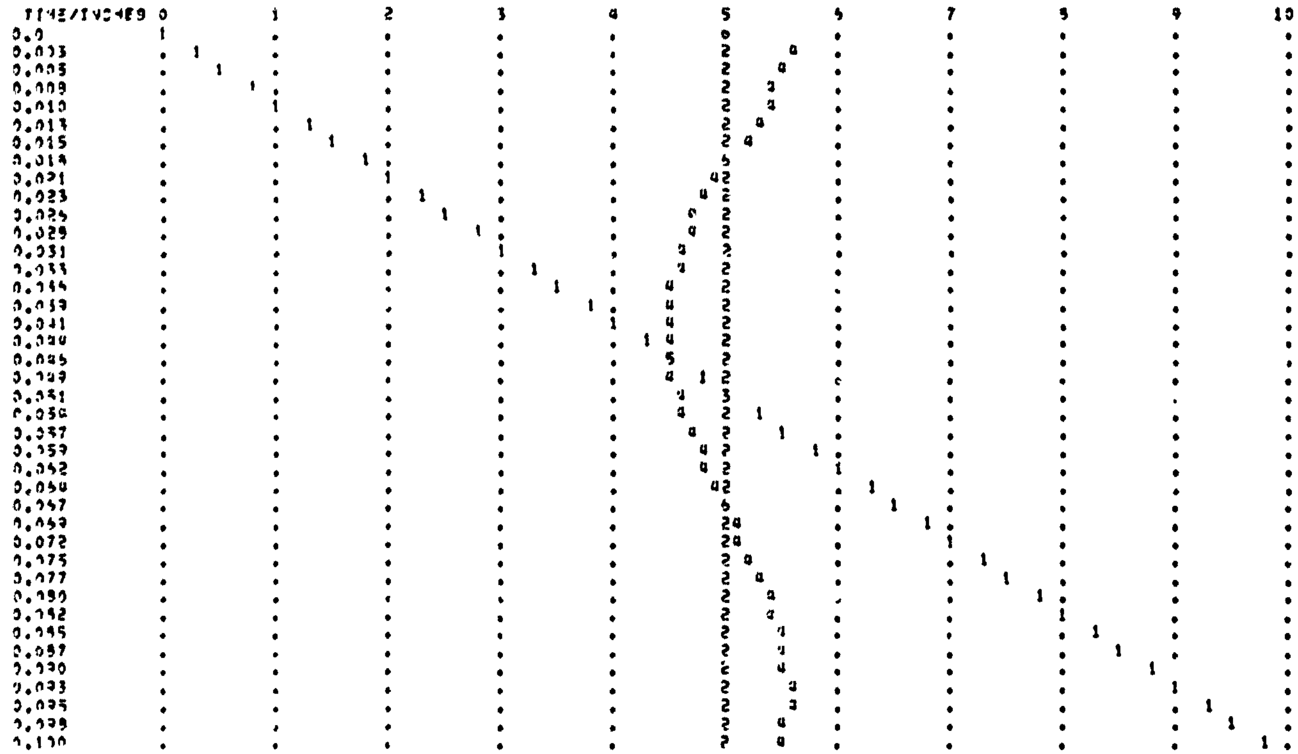

Figure 6. Concluded.

VALIDITY OF MATHEMATICAL MODEL

It must be emphasized that the validity of the correlation presented here, as well as the mathematical model of any other aircraft or rotor system, depends on two factors:

1. The adequacy of the technical analysis as implemented in the computer program.

2. The validity of the input data used to represent the physical characteristics of a particular aircraft.

References 1, 2, and 3 present the analysis in sufficient detail for the engineer to understand the assumptions it contains. The input deck also contains assumptions that are not always clearly visible from the computed results. Experience has shown that in a large percentage of cases, failure of the Rotorcraft Flight Simulation to obtain a trim solution or to provide adequate correlation with test data is due to inadequate input data. The most frequently made and most successfully used suggestion for users experiencing difficulty in running the program is "Check your input data." In other words, it takes

C-81	+	Input Data	=	Math Model

to represent the aircraft, and the user must do his part.

CORRELATION WITH TEST DATA

The correlation data presented in this section demonstrate some of the virtues and vices of the Rotorcraft Flight Simulation. They also reflect the ability of the user to prepare input for the program.

Performance

The 1/7.5 scale CH-47C model rotor correlations presented in Figures 7 through 12 are instructive, since they isolate the rotor and require the minimum amount of input data. Although the predicted slopes of the thrust-control axis angle curves in Figures 7 and 10 do not agree well with test results (possibly due to wake effects), the correlations in the other figures of this set show that performance prediction, in general, is good and that prediction of gross or total aircraft parameters is likely to be acceptable. These curves also show the effect of the Boeing-developed dynamic airfoil prediction method on the overall analysis.

Figures 13 through 16 show that total aircraft level-flight performance prediction is very good for single-rotor aircraft. However, Figures 17 and 18 show that for tandem-rotor helicopters, correlation is good only for the forward rotor. The interference effects on the aft rotor are not accounted for in the analysis. A simple interference correction developed by Boeing-Vertol results in a much improved power correlation.

Loads

Looking at the rotor analysis in greater detail, Figures 19 through 26 show that although peak-to-peak loads are predicted accurately, the azimuthal variations of both loads and lift coefficient lack agreement with experimental wave forms. This may again be due to wake approximations that predict a more regular inflow than actually exists.

Maneuver

The predicted maneuver for a CH-47C pull-up in Figure 27 agrees well with flight test data. In this figure, the three-per-rev has been removed from the test data by filtering, while it has not been removed from the computed results. The Bell Helicopter Company Model 583 pitch response correlation shown in Figure 28 shows a similar degree of correlation.

Stability and Control

The Rotorcraft Flight Simulation has been used extensively with a high degree of confidence by Bell Helicopter Company to predict aircraft stability and control characteristics for a number of years. Figures 29, 30, and 31 show typical stability and control correlation with flight test data. The good agreement between theoretical and flight test data shown in these figures suggests that Bell's confidence in this area of the analysis was justified.

FUTURE CORRELATION

Several detailed and systematic correlation efforts using the Rotorcraft Flight Simulation have been planned for the near future. The first is the Bell Helicopter Company correlation with H 34 model rotor data mentioned in the following section. In conjunction with the high-speed maneuverability flight test of their flex-beam (hingeless) rotor system, Bell will also correlate the C-81 predicted aircraft performance and loads with the test data.

A third correlation will be conducted by the Eustis Directorate staff in conjunction with the maneuverability and flight loads flight test of the AH-1G to be conducted for the Government by Bell. This effort will follow the 2-year flight test program that is scheduled to start in the near future.

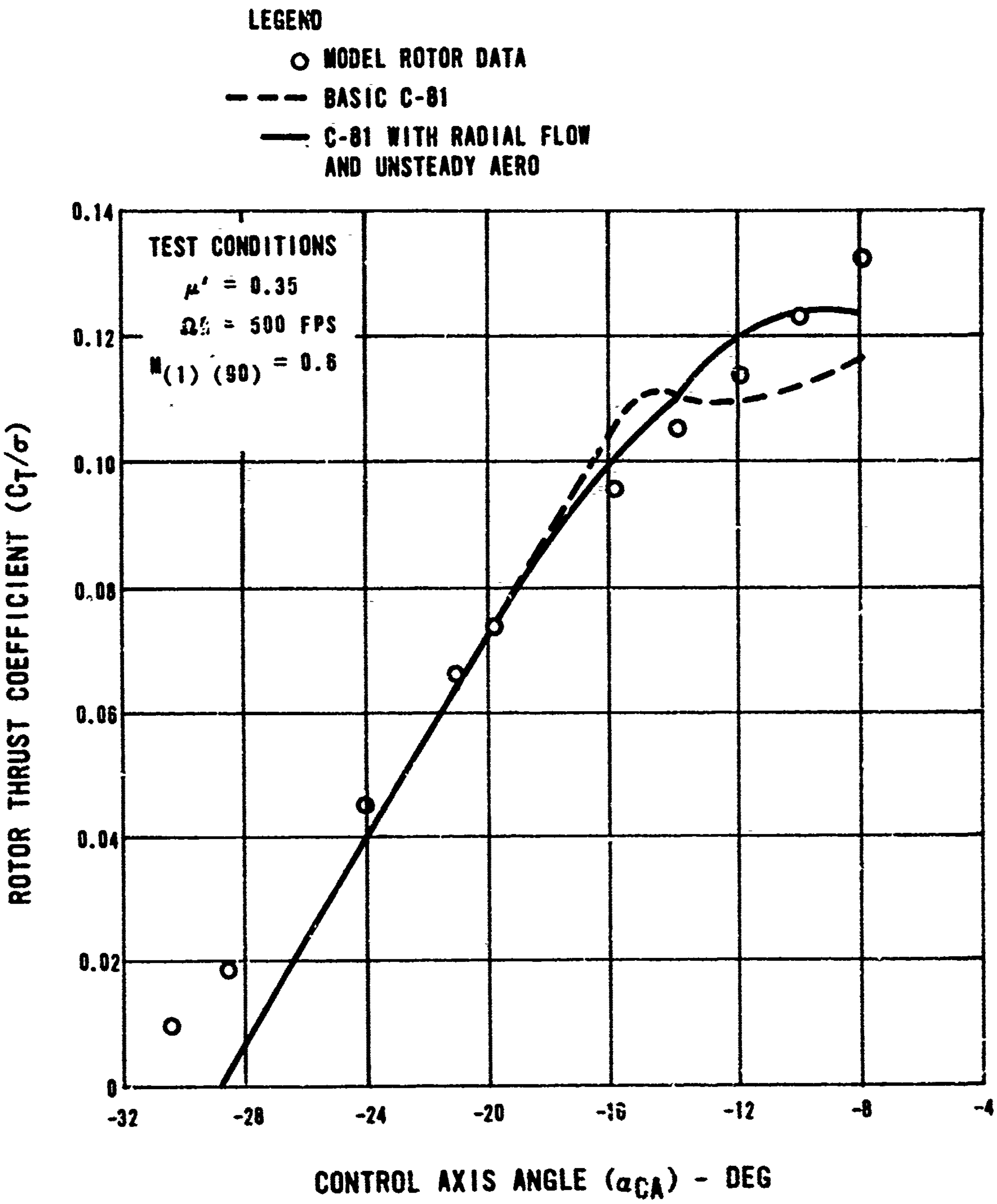

Figure 7. Model Rotor Correlation With Rigid Blade Rotor Theory: Rotor Thrust vs Control Axis Angle.

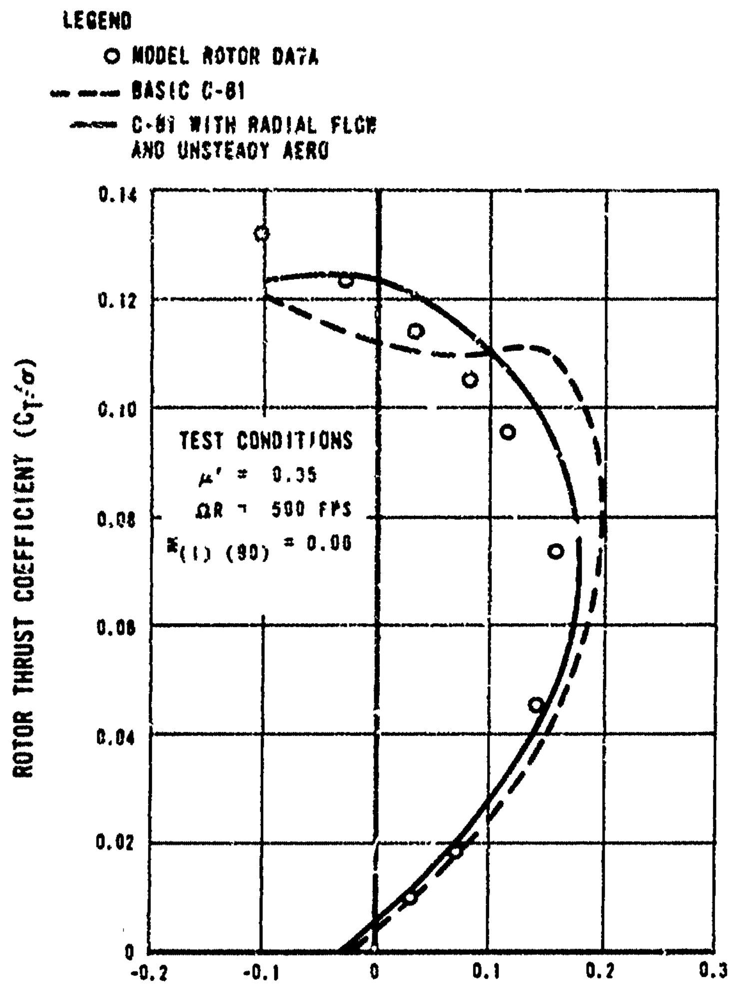

Figure 8. Model Rotor Correlation With Rigid Blade Rotor Theory: Rotor Thrust vs Rotor Propulsive Force.

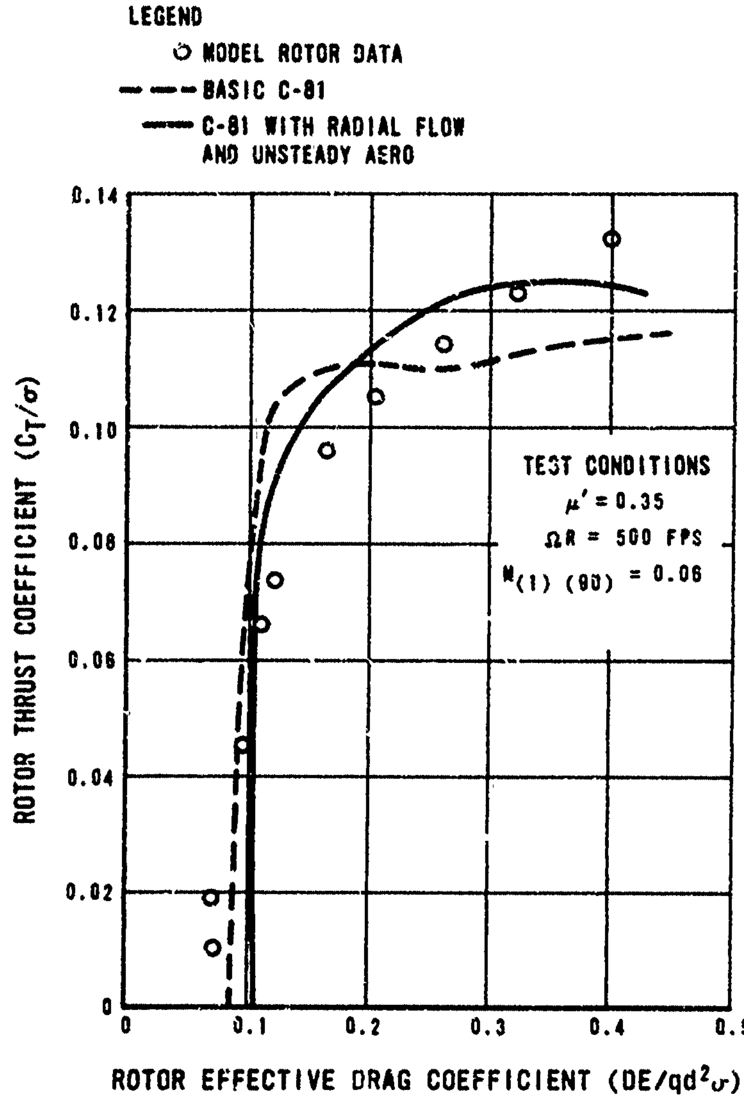

Figure 9. Model Rotor Correlation With Rigid Blade Rotor Theory: Rotor Thrust vs Rotor Effective Drag.

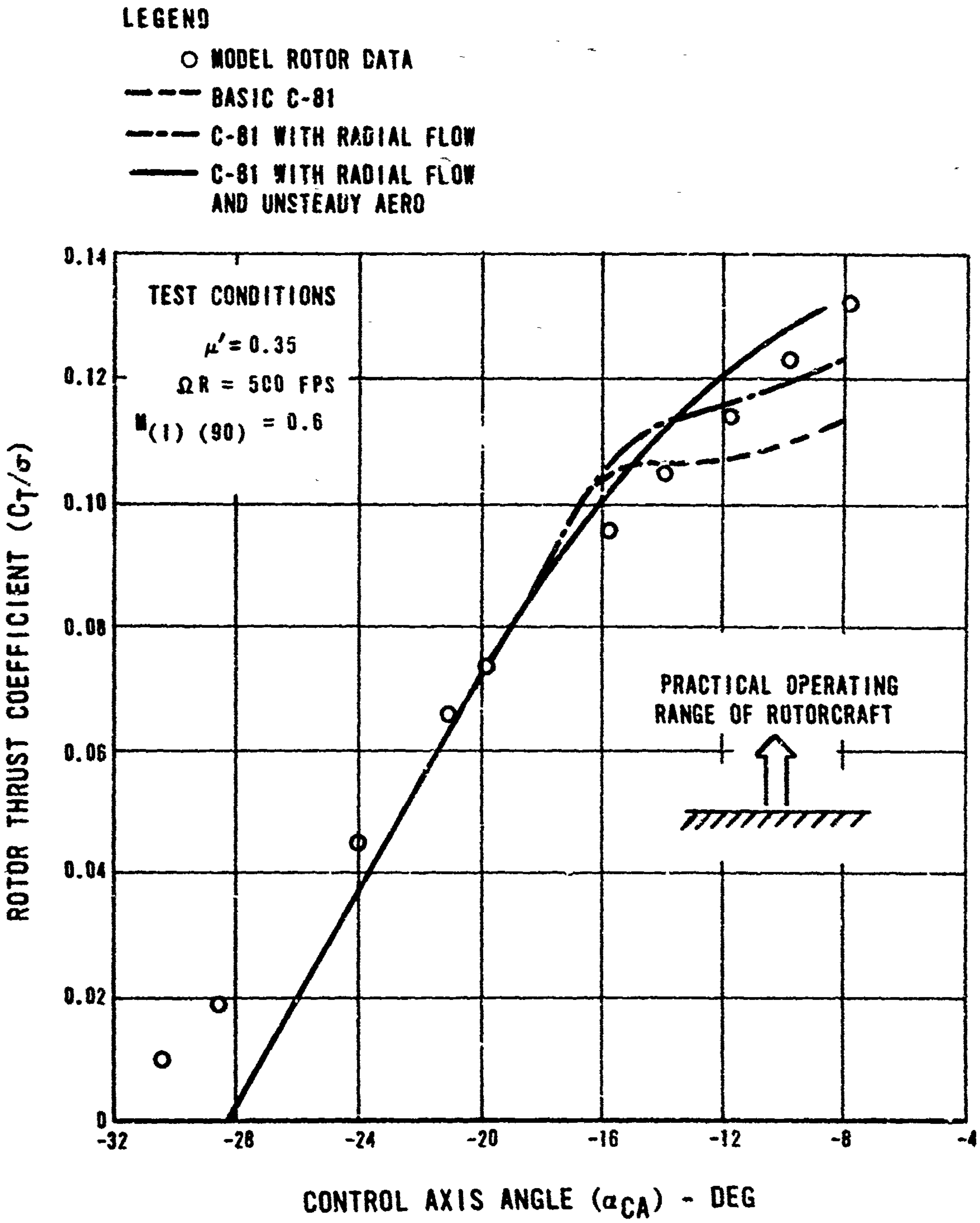

Figure 10. Model Rotor Correlation With Elastic Blade Rotor Theory: Rotor Thrust vs Control Axis Angle.

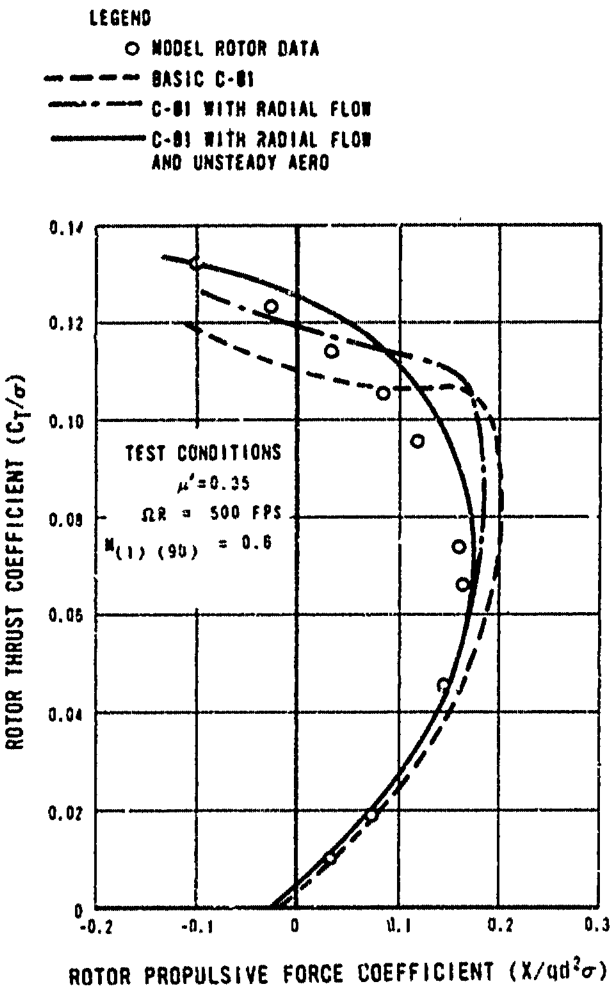

Figure 11. Model Rotor Correlation With Elastic Blade Rotor Theory: Rotor Thrust vs Rotor Propulsive Force.

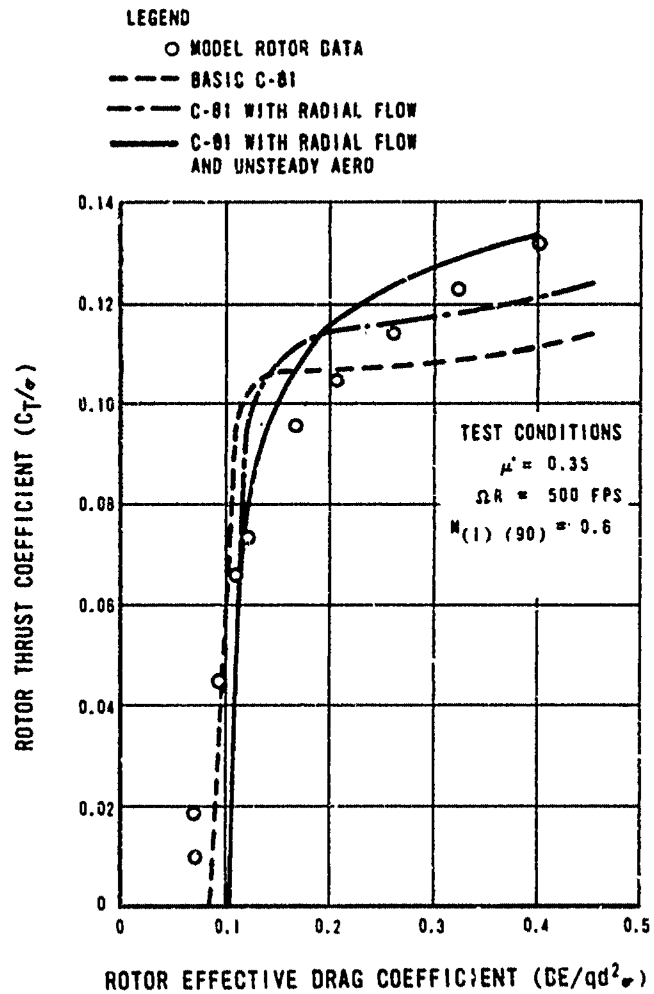

Figure 12. Model Rotor Correlation With Elastic Blade Rotor Theory: Rotor Thrust vs Rotor Effective Drag.

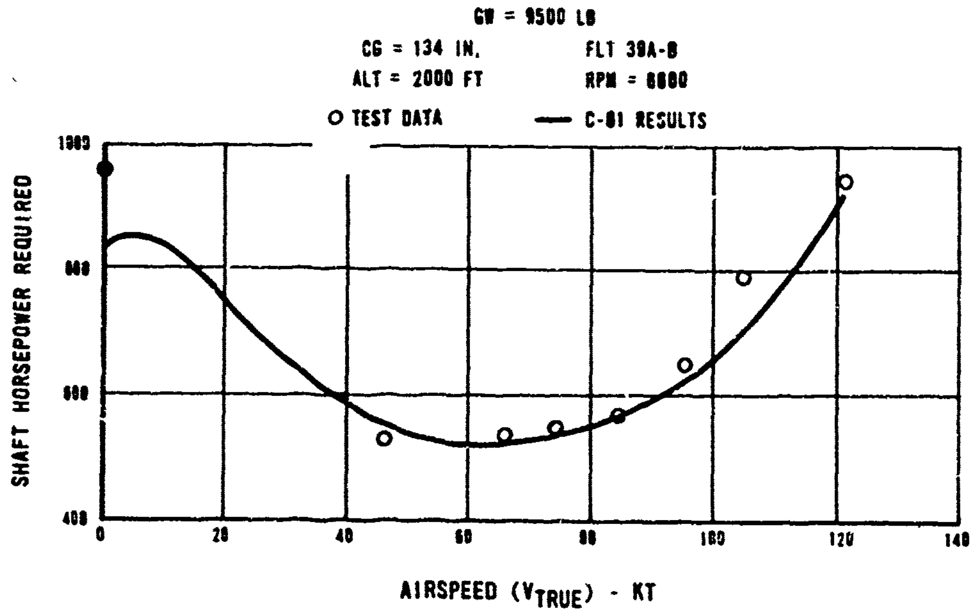

Figure 13. UH-1D Level-Flight Performance Correlation.

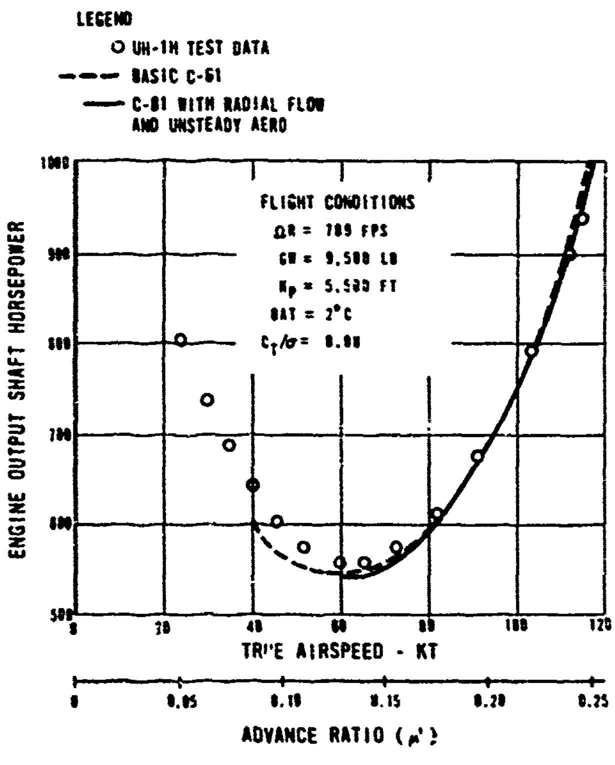

Figure 14. Correlation of Theory With UH-1H Test Data.

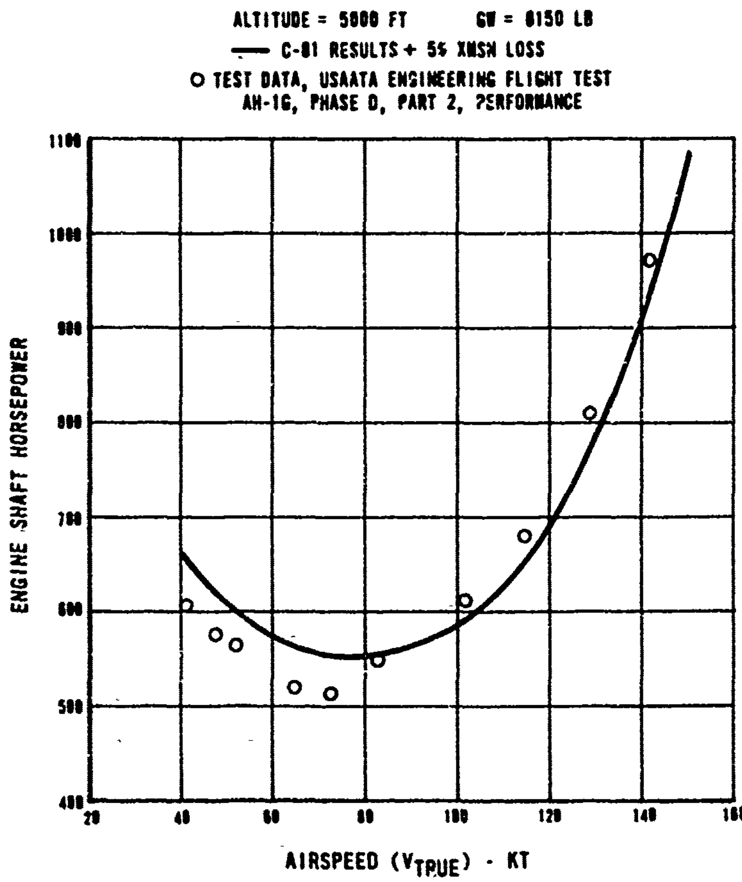

Figure 15. AH-1G Level-Flight Performance Correlation.

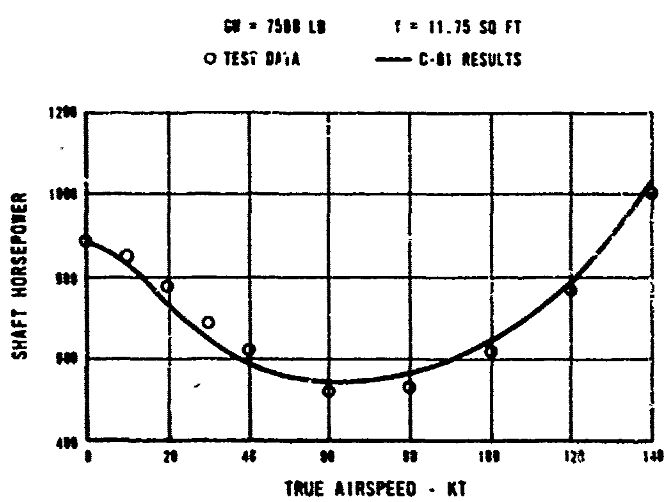

Figure 16. AH-1J Level-Flight Performance Correlation.

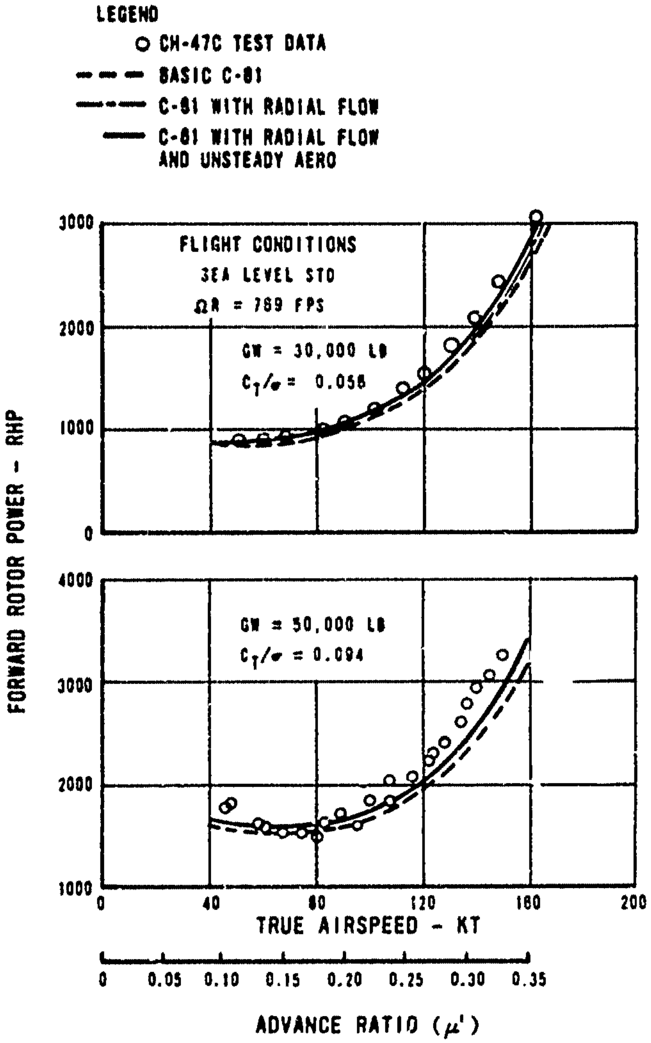

Figure 17. Correlation of Theory With CH-47C Forward Rotor Test Data.

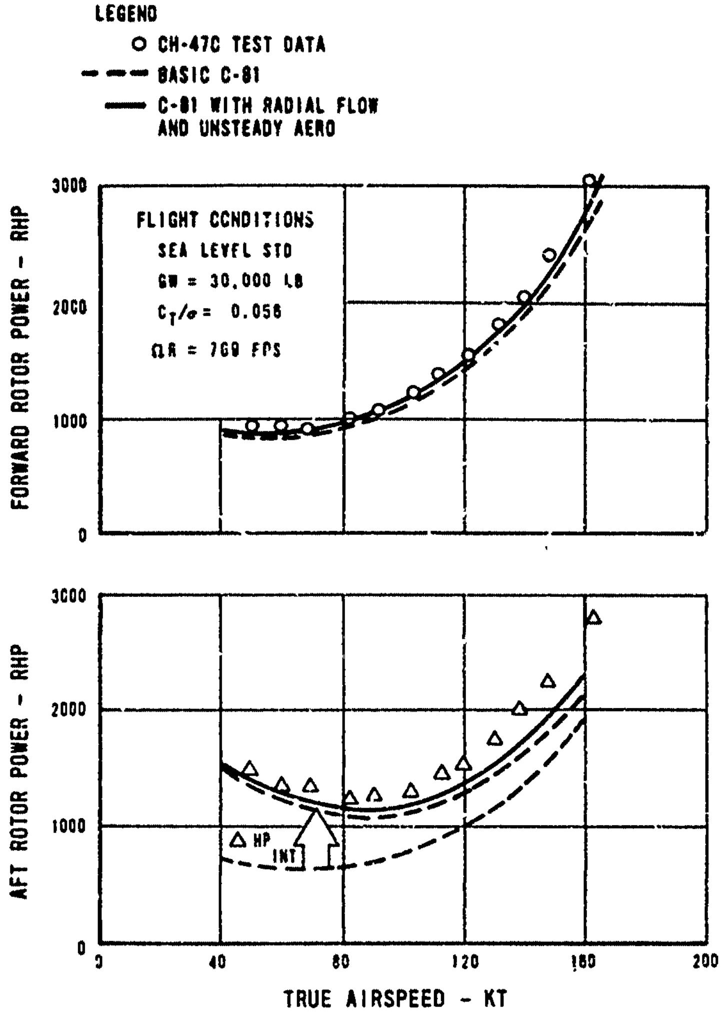

Figure 18. Correlation of Theory With CH-47C Test Data.

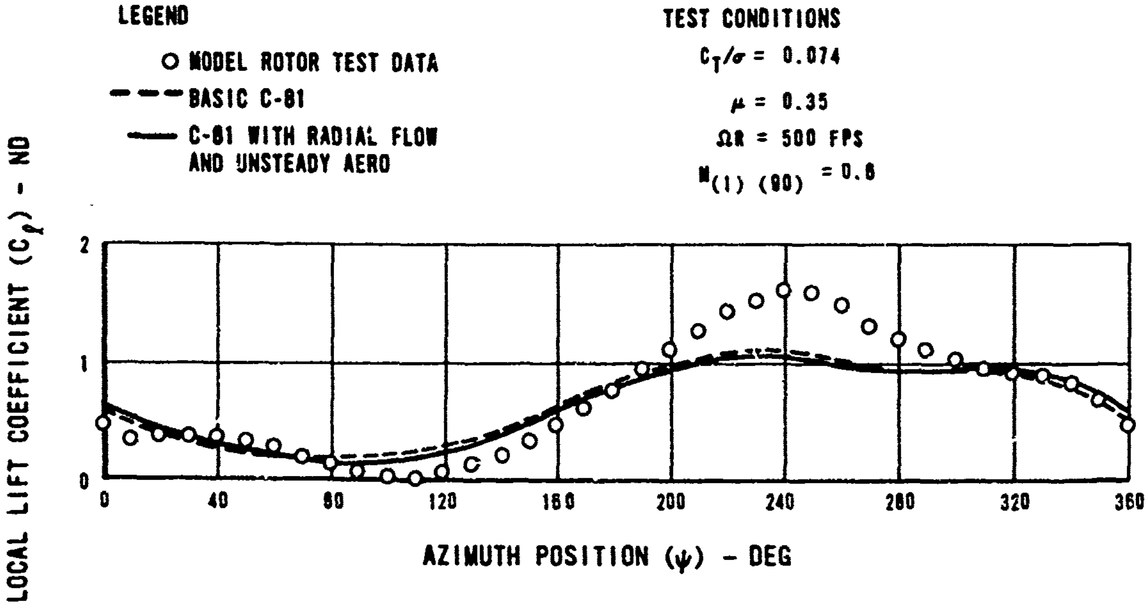

Figure 19. Model Rotor Correlation With Azimuthal Coefficient-of-Lift Variation at 0.75 Radius (C_T/σ = 0.074).

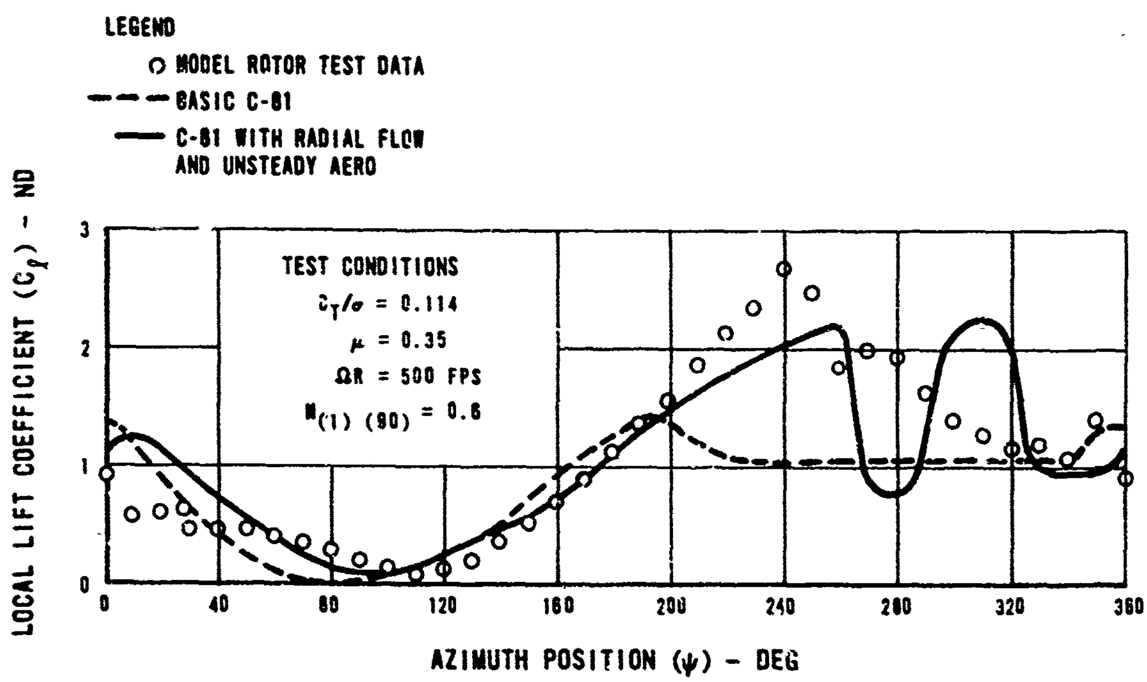

Figure 20. Model Rotor Correlation With Azimuthal Coefficient-of-Lift Variation at 0.75 Radius (C_T/σ = 0.114).

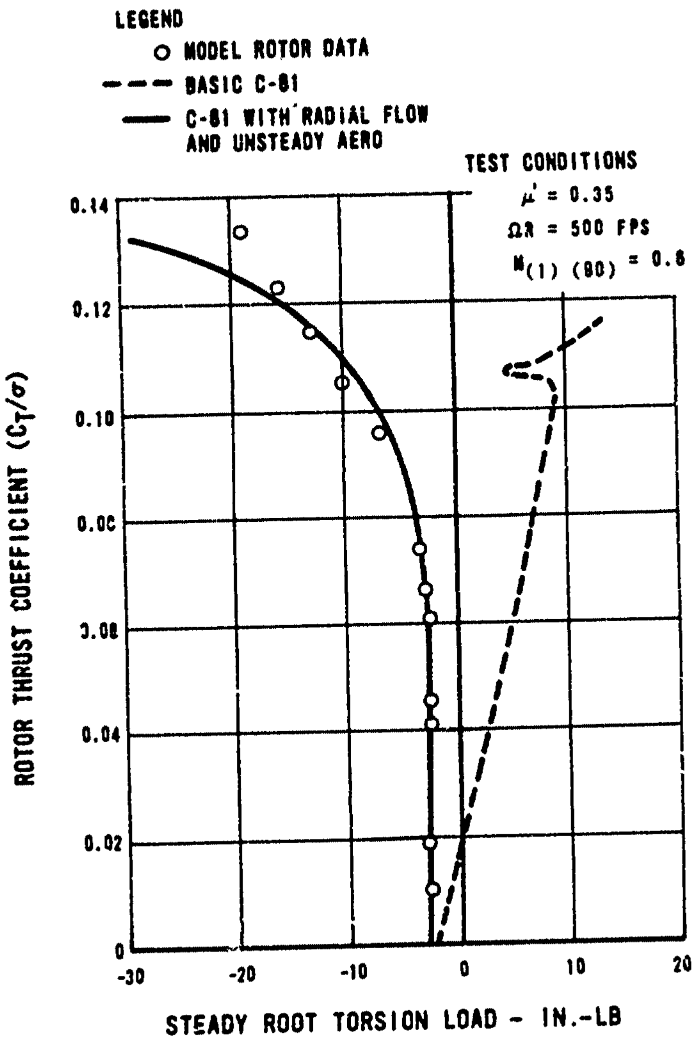

Figure 21. Model Rotor Correlation With Elastic Blade Rotor Theory: Rotor Thrust vs Steady Root Torsion Load.

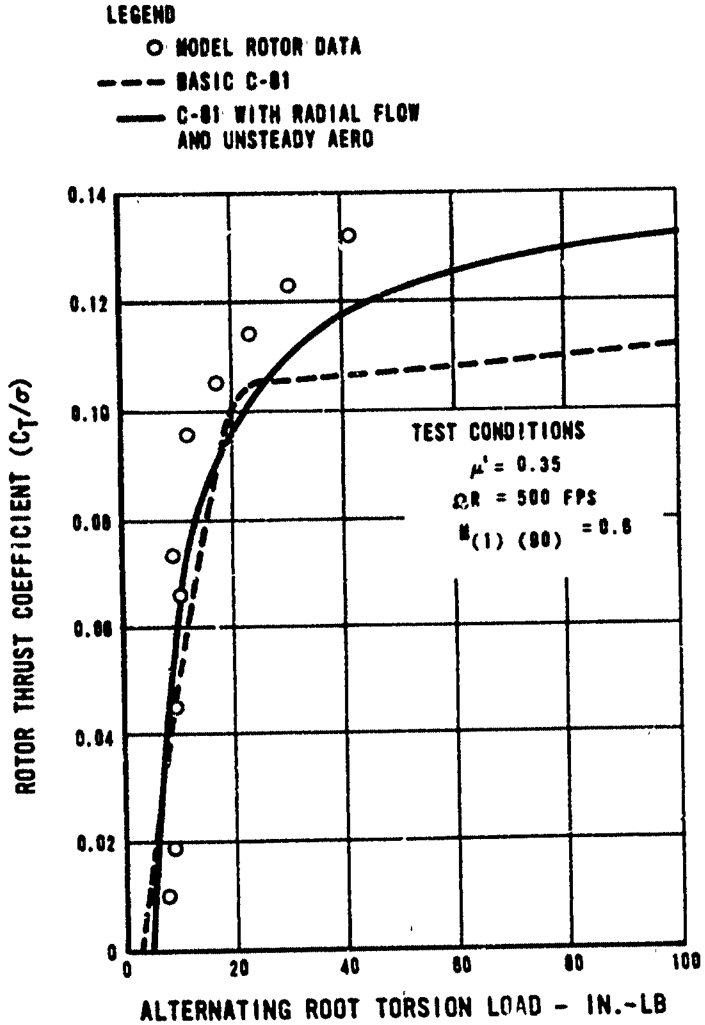

Figure 22. Model Rotor Correlation With Elastic Blade Rotor Theory: Rotor Thrust vs Alternating Root Torsion Load.

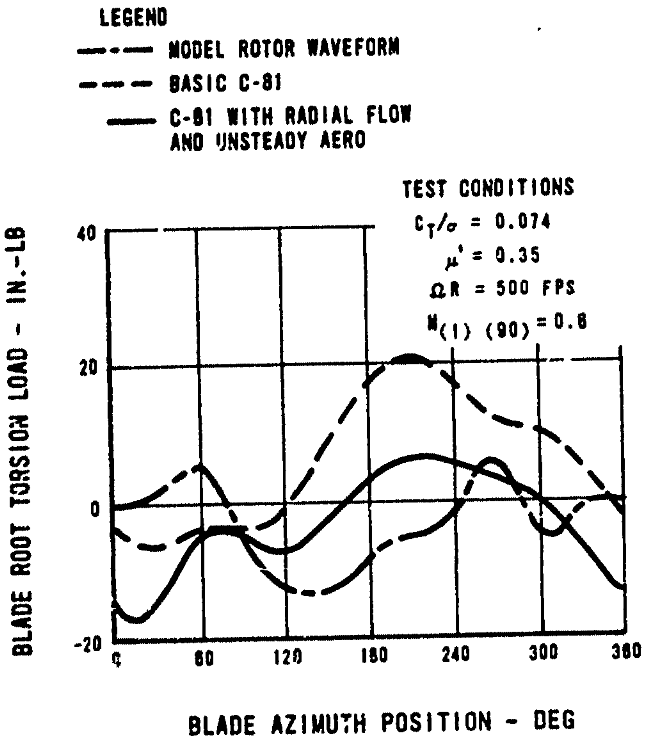

Figure 23. Correlation of Theory and Model Rotor Blade Root Torsion Loads: Blade Root Torsion Load vs Blade Azimuth Postion (C_T/σ = 0.074).

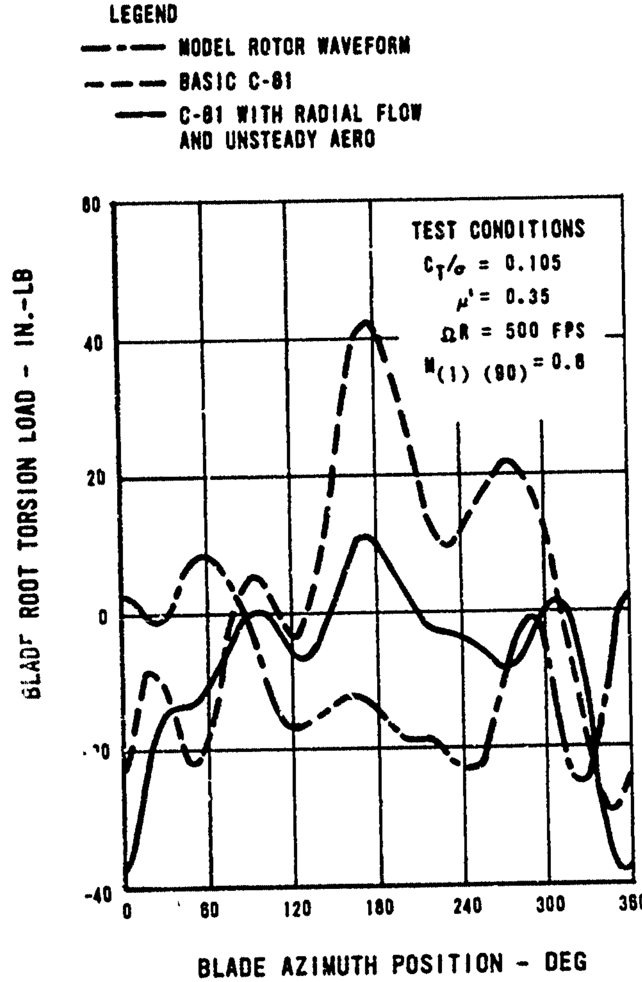

Figure 24. Correlation of Theory and Model Rotor Blade Root Torsion Loads: Blade Root Torsion Load vs Blade Azimuth Position (C_T/σ = 0.105).

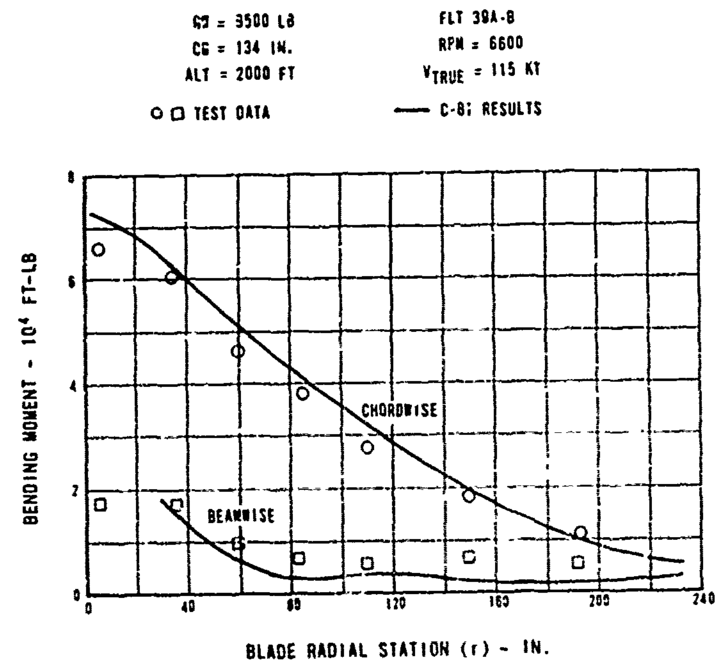

Figure 25. UH-1D Oscillatory Loads Radial Distribution.

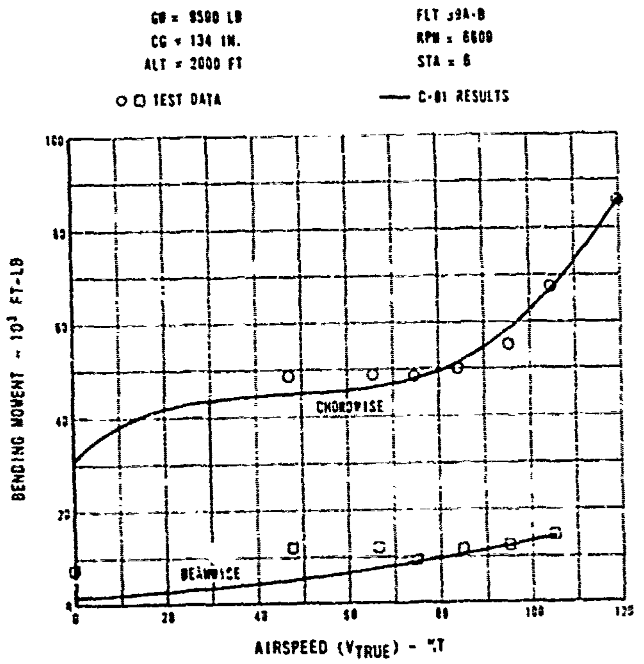

Figure 26. UH-1D Oscillatory Load Variation With Speed.

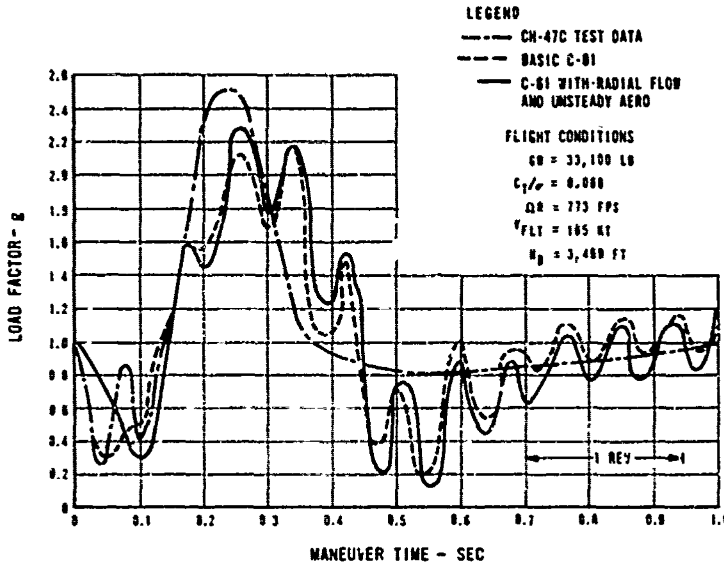

Figure 27. Correlation of Theory With CH-47 Pull-up Maneuver.

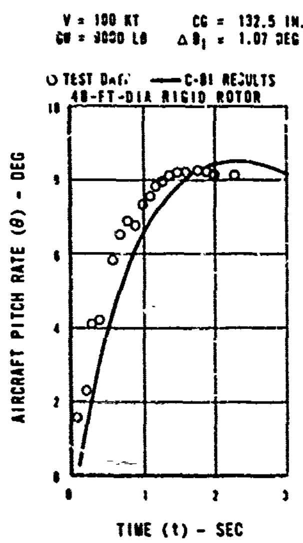

Figure 28. Bell Model 583 Pitch Response.

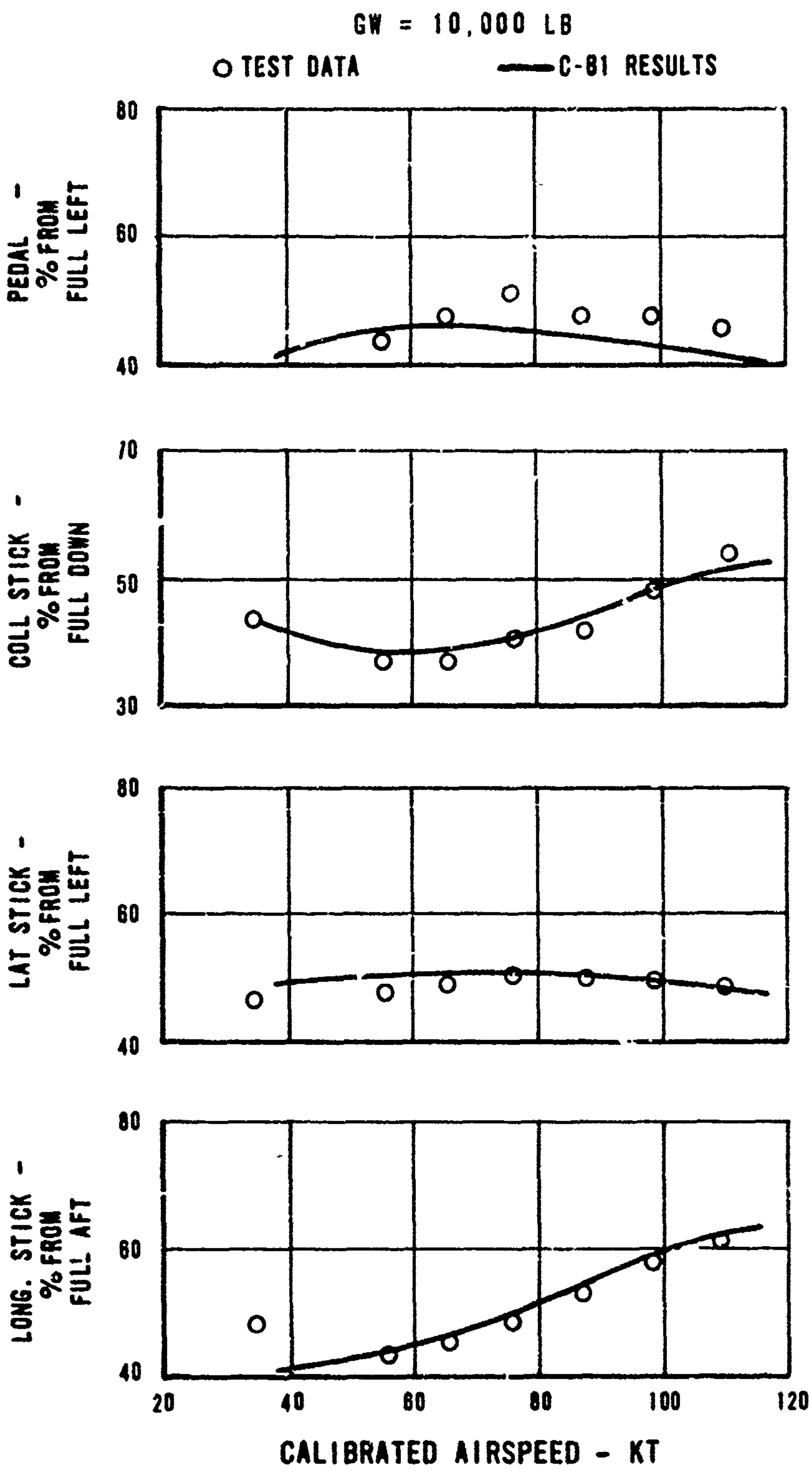

Figure 29. UH-1N Level-Flight Speed Stability.

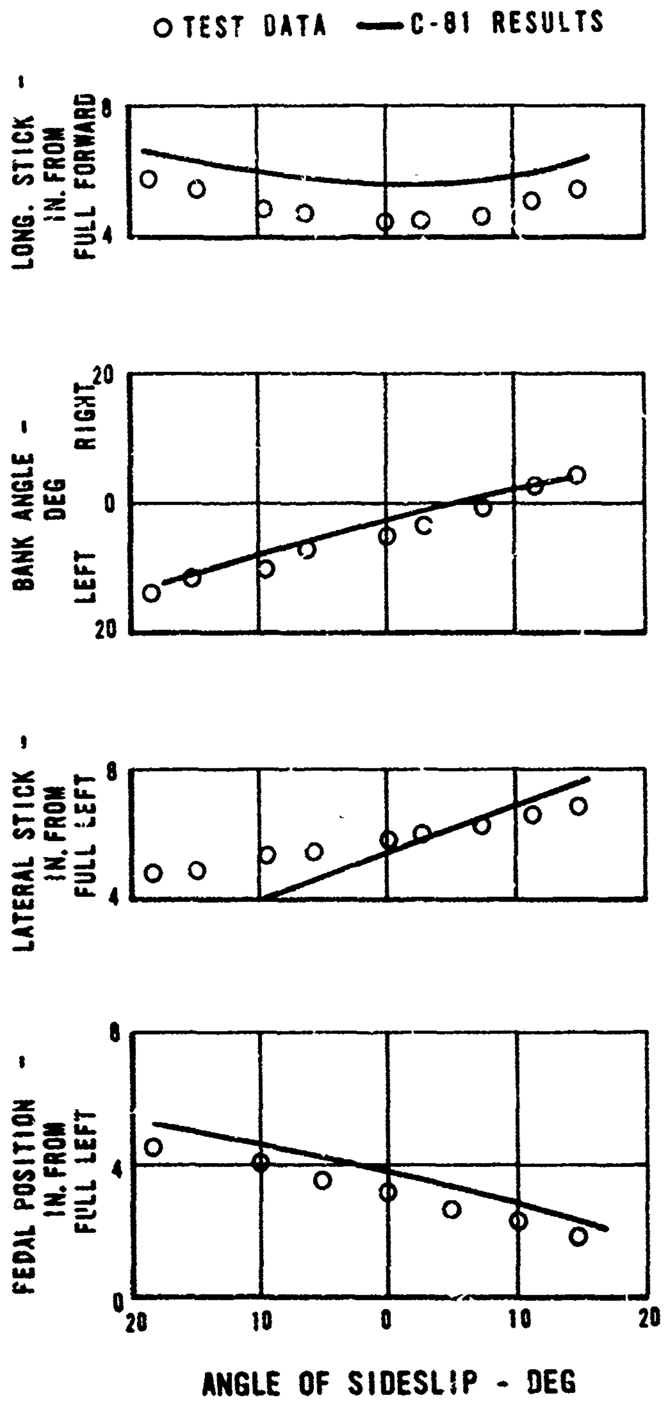

Figure 30. OH-58A Static Lateral-Directional Stability in Level Flight.

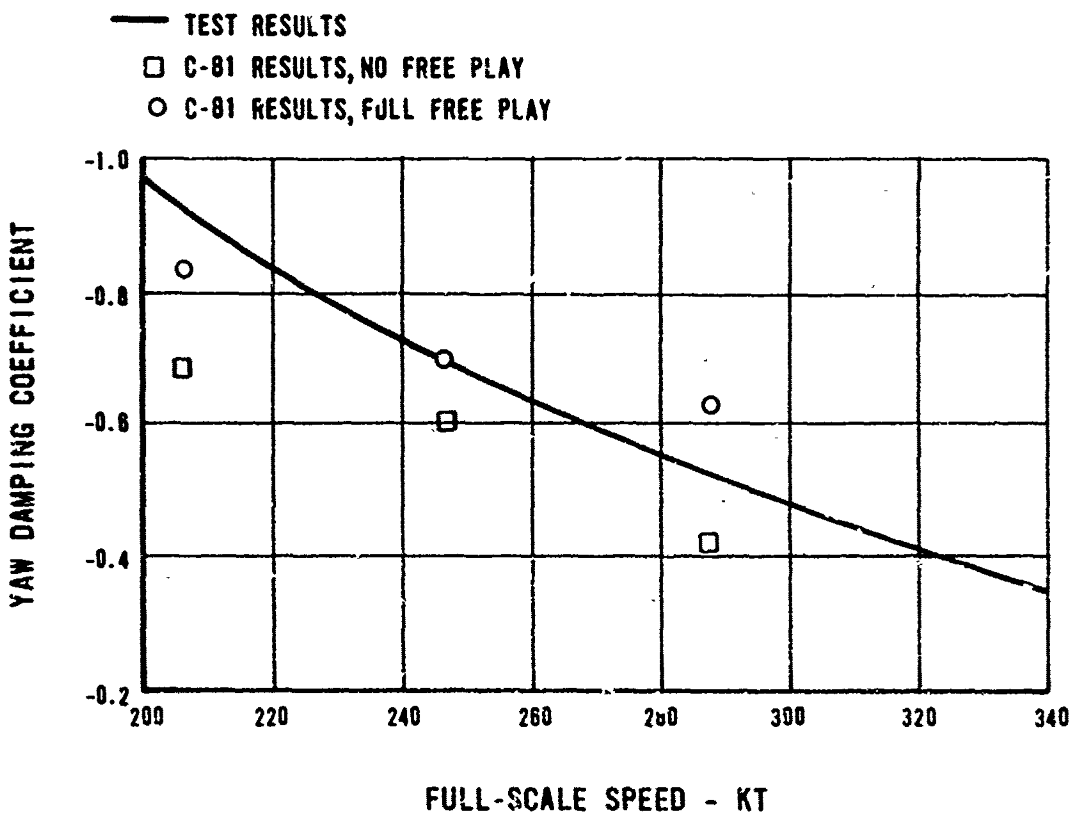

Figure 31. 1/12 Scale Twin Proprotor Effect of Free Play in Interconnect Shaft on Aircraft Yaw Damping.

CURRENT DEVELOPMENT

UNSTEADY AERODYNAMIC EFFECTS

Vertol Division, The Boeing Company (under Contract DAAJ02-71-C-0045) has developed for use with the Rotorcraft Flight Simulation, methodology for evaluating and predicting the aerodynamic force and moment coefficients of an airfoil in an unsteady flow environment. The method is especially useful, since it is not dependent on constants that must be derived from wind tunnel tests for each new airfoil shape. The analysis has been incorporated into the 1971 CDC 6600 version of the program, and the final report will be published in the near future. The analysis will be included in the 1972 version of the program as an in-house project during 1973.

HELICOPTER MATHEMATICAL MODELING FOR CONTROL SYSTEMS

Under a contract to Honeywell, Inc. (DAAJ02-71-C-0053), an improved mathematical tool to evaluate future helicopter control systems is being developed. The program will be extended to include the capability to simulate fluidic stability augmentation systems, electronic autopilot systems, and control moment gyros. The contractor will also provide a general optimal control system design for demonstration with the program. The program analysis will be extended to calculate linear data for linear analysis and design and a trim procedure that facilitates convergence.

ROTORCRAFT FLIGHT SIMULATION WITH AEROELASTIC ROTOR REPRESENTATION CORRELATION

Bell Helicopter Company (under Contract DAAJ02-72-C-0086) will establish the capability of the program to predict helicopter rotor performance and loads and will isolate areas of the rotor analysis that need refinement. This will be accomplished by performing a correlation study in conjunction with the H-34 model rotor wind tunnel tests to be conducted by Sikorsky Aircraft under Contract DAAJ02-72-C-0026. Pretest predictions will be made to establish the ability of the program to predict rotor performance and loads from design data. Additional correlation will be performed after the test so that exact test points may be matched.

IMPROVED AERODYNAMICS AND AEROELASTIC REPRESENTATION FOR THE ROTORCRAFT FLIGHT SIMULATION

Under Contract DAAJ02-72-C-0098, Bell Helicopter Company will improve the program in the areas of aerodynamic representations and numerical integration techniques. New or improved methods for mathematically modeling the aerodynamic forces and moments acting on a helicopter fuselage, stabilizing surfaces, wings, external stores, and rotor blades will be developed. Mathematical techniques for solving sets of differential equations typical of those found in helicopter aeroelastic analyses will also be studied. A more efficient program able to model more types of aircraft in a larger number of tactical maneuvers will result from this program.

FUTURE WORK

It is apparent that the analytical sophistication in at least two areas of the program does not match the refined aeroelastic rotor analysis. That is, the program is not of totally uniform texture. The first is in the representation of the rotor inflow and wake. The simplified equations expressing inflow velocity as a function of radius, azimuth, thrust, and flight path are not adequate to predict rotor performance and loads at low airspeeds. Rotor/rotor, rotor/wing, and rotor/tail interference effects all need to be predicted more accurately for loads and stability and control.

The other nonuniform area of analysis is in fuselage dynamics. The present rigid-body assumption should be replaced with an elastic fuselage representation. Studies of aircraft vibration levels could be performed using the program if an elastic fuselage representation were added. This addition would also permit more accurate prediction of tail rotor angle of attack that is necessary for all tail rotor investigations.

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